RESPONSES OF HIGH BIOMASS RICE (*ORYZA SATIVA* L.) TO VARIOUS ABIOTIC STRESSES

A Thesis

by

ADITI NITINKUMAR KONDHIA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2010

Major Subject: Plant Breeding

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Co-Chairs of Committee,	Rodante E. Tabien
	Amir M.H. Ibrahim
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ABSTRACT

Responses of High Biomass Rice (*Oryza sativa* L.) to Various Abiotic Stresses. (August 2010)

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Co-Chairs of Advisory Committee: Dr. Rodante E. Tabien
Dr. Amir M.H. Ibrahim

Rice produces a lot of biomass which is an important trait in increasing grain yield and it is a potential feedstock for bioenergy production. High biomass rice is important to meet the growing demands of grains and biomass for food, fodder and bio-fuel industries. Limited studies have been conducted to determine its response to unfavorable conditions. The main objectives of this study were to determine the response of selected high biomass rice to drought, rainfed and flooded conditions and identify best genotypes that can be grown in unfavorable areas. Two experiments were conducted in summer 2009 to evaluate biomass yield and agronomic traits of selected high biomass genotypes. A greenhouse study had genotypes grown under drought condition - different field capacity (FC) i.e. 100%, 75% and 50% FC, while the field study had rainfed and flooded environments.

Most of the genotypes performed well under fully saturated soil conditions but some were less affected by drought. Limited water delayed first tiller emergence and reduced tiller count, rate of tiller production, plant height, rate of increase in height, shoot and root weight, root:shoot (R:S) ratio, percent dry matter (% DM) and total

biomass. The plant height, tiller plant^{-1}, and total biomass at maturity were lower under rainfed conditions and their flowering was delayed compared to flooded conditions. Majority of these traits were correlated with high biomass yield. Genotype 11 which is tall and late maturing produced the highest number of tillers plant^{-1} and tillers/ 750 cm^2 and had the highest biomass yield under both rainfed and flooded conditions. It performed equally well under drought conditions particularly in root and R:S ratio, but genotype 12 was the best in most parameters measured in the greenhouse. Although it was the shortest genotype, it was highest in biomass yield, earliest to tiller, had the highest shoot weight and tiller count, and had the fastest tiller production. The high biomass genotypes like conventional rice were affected by drought and performed better under flooded conditions. However, these two genotypes can produce optimum results under limited availability of water and hence be used for biomass production under stressed environments.

DEDICATION

I would like to dedicate this research to my parents,

NITIN KONDHIA and CHETNA KONDHIA,

my husband,

HIREN PANCHAL,

and my brother and sister,

VISHAL and PURVI

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NOMENCLATURE

DAS	Days After Sowing
FC	Field Capacity
FW	Fresh Weight
DW	Dry Weight
R:S	Root:Shoot
% DM	Percent Dry Matter

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CHAPTER I

INTRODUCTION

Rice (*Oryza sativa*) is one of the most important food crops belonging to the grass family (Poaceae). Rice is also the staple food for a large part of the world's human population, is the most consumed cereal after wheat, and has the second largest area under production following maize worldwide. It is considered as the world's most diverse and versatile crop as it can be found from 53^0 North in Northeastern China to 35^0 South in New South Wales, Australia (Mae, 1997; Santos et al., 2003). Rice is generally an annual plant but in some tropical areas it survives as a perennial and produces ratoon for several years. Rice can be grouped into *indica*, *japonica* and *javanica* types. *Javanica* known also as "tropical japonica" (Mae, 1997) is the type of rice commonly grown in the U.S. The first trial conducted on rice in the U.S. was established in Virginia in 1609 but the commercial cultivation started in South Carolina around the same time. Today, rice is being in six states of the USA including Arkansas, California, Louisiana, Mississippi, Missouri and Texas.

Rice plant growth is mainly divided into three different stages: vegetative, reproductive and grain filling or ripening stage (Wang and Li, 2005). The vegetative stage, extending from germination to the initiation of panicle primordial, is characterized

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This thesis follows the style and format of Crop Science.

largely by tiller formation and the determination of potential panicle number unit^{-1} area. The reproductive stage occurs from panicle initiation to flowering. During this stage, the spikelet number and their potential sink size is determined largely by plant nutrition and environmental factors. The ripened grain and grain size is determined during this developmental stage. The ripening stage of the rice is defined as grain filling or hardening of the grains. Grains contain lowest amount of moisture at the ripening stage. The duration of each growth stage is influenced by variety, plant nutrient supply, agronomic practices and climatic conditions, and these factors affect biomass and grain production.

Different environments have different effects on the production of rice grain and biomass. Rice grown in humid tropics, in rainfed (dry land) areas that cover 9% of the total area in which rice is grown (IRRI, 1993), may suffer drought, acidity of soil and deficiency of phosphorus and zinc. Drought is one of the most important limiting factors in the production of the major crops in the world. The percentage of drought affected land areas has doubled from 1970 to early 2000 (NCAR-UCAR, 2005). Drought causes yellowing of leaves, reduces number of tillers, height of plant, number of panicles and overall vegetative weight and increases number of unfilled grains. The total biomass production was increased up to 32% in intermittent irrigation treatment in rainfed fields and the root length and dry matter were positively affected by intermittent irrigation (Gani et al., 2002). In tropical regions where rice is grown in monsoon (rainy) climate, there is possibility of flooding and non-flooding. Chaudhry and McLean (1963) reported that there were more productive tillers plant^{-1} under flooded than non-flooded (rainfed) conditions. If rice is grown during the dry season in tropical countries where adequate irrigation is available, the crop could suffer from low temperature during seedling stage and high temperature at flowering stage. In coastal regions, rice can be exposed to salinity stress. Salinity may result in significant reduction in seedling growth and survival and may lead to major grain and biomass yield loss (Yeo et al., 1990). When rice is grown in fully irrigated temperate regions, cold is a major abiotic stress that will affect rice yields.

One of the most important sources for renewable energy is crop biomass (Kirubakaran et al., 2009) and the potential of biomass to meet the world energy demand has been widely recognized. One third of the primary energy sources after coal and oil are biomass (Werther et al., 2000). Rice is a potential source of feedstock for bio-refinery since it can produce a lot of biomass. It can also be a dedicated feedstock; however, it should not compete for areas favorable for grain production. There are many unfavorable areas for rice production that can be tapped for high biomass production. Hence, our goal was to study the response of high biomass rice grown under stress conditions so that adapted genotypes can be grown in unfavorable environments for biomass and grain production. The main impact of this study is the generation of base information on high biomass rice genotypes which is important for the future bioenergy related research activities. The evaluation of agronomic traits will be useful in crop improvement and in basic research to understand their relationship with high biomass production. It will help us understand the science needed to achieve high stable biomass yields under unfavorable environments. The main objective of this study was to determine the response of selected high biomass rice genotypes to drought and rainfed growing condition. Specifically, the study aimed to determine growth and biomass yield of selected *O. sativa* lines under two levels of drought and their agronomic response in rainfed and flooded conditions.

CHAPTER II

REVIEW OF LITERATURE

2.1 Rice as Source of Biomass

Traditionally, the biomass of rice is a very useful by-product after following the grain harvest. It can be used as mulch and help in conserving moisture and erosion control or compost and bedding for livestock. Biogas can be generated from rice straw. With catalytic activity of anaerobic bacteria, these residues are broken into organic compounds which can directly be converted to methane, the gas that can be stored and used as a source of energy in farm households. Rice post-harvest residues can be feedstocks in generating bioenergy (Kadam et al., 2000). Rice hull, a major by-product of rice milling industry is a potential source of energy (Lin et al., 1998). By harvesting the rice residues, the developing countries can generate 5.80 x 10^{18} J $year^{-1}$ (Freedman, 1983). For instance, the energy potential from rice straw as renewable fuel is 311.6, 237.5 and 141.8 PJ for India, Thailand and the Philippines, respectively (Gadde et al., 2009).

Energy from biomass can be derived through thermo-chemical processes such as gasification, combustion and pyrolysis (Grassi et al., 1990). Gasification is an incomplete combustion of biomass resulting in the production of combustible gases called producer gas composed of carbon monoxide (CO), hydrogen (H_2) and traces of methane (CH_4). It is a promising technology that provides a competitive means of producing chemicals and energy from renewable energy sources (Chen et al., 2004;

Moghtaderi, 2007; Weerachanchai et al., 2008; Toonssen et al., 2008). The large biomass from rice hull and rice straws, are good feedstocks for gasification or cellulosic digestion. An alternative energy recovery to produce liquid hydrocarbons from biomass is by pyrolysis (Lin et al., 1998). Pyrolysis is a special case of thermolysis, the chemical decomposition of organic materials by heating at 200-300°C (390-570°F). The process produces gas and liquid products, and leaves a solid residue that is rich in carbon content.

2.2 Breeding and Cultivation of High Biomass Rice

Breeding for high biomass rice is being done in Japan through the development of forage rice as animal feed. In 2006, more than 5,000 ha were grown to forage rice in southwestern Japan (Nakano et al., 2009). Biomass quantity and quality in both grains and rice straws are considered before the release of the variety. Nakano and Morita (2007) found that forage rice variety Taporuri had the highest dry matter yield followed by Saikaishi, Mohretsu and Hinohikari.

The twice harvesting or ratoon cropping is the practice of obtaining a second crop from the stubble of the first crop (Jones and Snyder, 1987). Twice harvesting system has been used for rice cultivation in U.S. (Evatt and Beachell, 1960), Swaziland (Evans, 1957), India (Gupta and Mitra, 1948), Thailand and Taiwan (Iso, 1954), the Philippines (Parago, 1963), and China (Yang et al., 1958) but it was aimed to increase grain production rather than biomass harvest. Studies in forage rice, however, suggested that twice harvest can be beneficial in increasing biomass yield. The highest biomass yield of 27 t ha^{-1} was obtained at first harvest during heading, fertilized with 300 kg ha^{-1}

in a 4-way split (Nakano and Morita, 2007). In subsequent study, Nakano et al. (2009) reported that higher dry matter yield of the second crop was possible by increasing the cutting height after the first harvest at full heading. However, the dry matter of the first harvest decreased with increasing cutting height and the overall total dry matter yield did not vary with the cutting height. It was noted that it is necessary to develop an efficient twice harvesting method for the production of forage rice because forage rice must have low production cost (Nakano et al., 2009).

Among agronomic traits studied, a significantly positive correlation was observed between dry matter yield of the first crop with the duration of vegetative growth and the weight tiller^{-1} but not with tillers square meter^{-1} (Nakano and Morita, 2007). Relative to cutting height, however, the number of tillers square meter^{-1} and the dry weight tiller^{-1} increased with increasing cutting height (Nakano et al., 2009). The long growth duration variety is generally associated with higher dry matter yield than those with short growth duration, and variety are with long duration of vegetative growth and high weight tillers^{-1} in the second crop produce high dry matter yield in the second crop (Nakano and Morita, 2007). Increased straw yield was found weakly related to greater stem weight although greater stem weight indicated decreased stand density (Summers et al., 2003). Plant height, erect leaves and tiller number are important plant architectural traits in increasing biomass (Yuan et al., 2008; Salas-Fernandez et al., 2009).

It is commonly accepted that most modern semi-dwarf rice varieties have a 1:1 straw to grain ratio whereas the traditional tall varieties yields have more straw, with ratio greater than 2 (Yoshida, 1981). Evaluating U.S. released varieties for biomass distribution, Summers et al. (2003) reported that the internode section of the stem had 40% biomass, 53% in leaf and sheath, 4% in nodes and 3% in panicle excluding hull and seed and when the plants were cut at 30 cm, the fractions were 69% leaf and sheath, 22% internodes, 4% node and 5% panicle.

2.3 Rice Biomass and Grain Yield

Biomass accumulation is important in increasing grain yield and breeding for high biomass was proposed as a way to enhance yield in grain crops (Boukerrou and Rasmusson, 1990). Grain yield increases in rice were attributed to the improvements in both biomass and harvest index (Zhang et al., 2004). Verma and Srivastava (2004) reported that higher yield was associated with traits like harvest index, biomass yield, 100 grain weight and productive tillers plant^{-1}. Recent studies showed that both accumulation of higher biomass at each phenological phase of rice (Bueno and Lafarge, 2009) and better dry matter partitioning (Lafarge and Bueno, 2009) were the basis of 14-18% grain yield advantage of hybrids over inbreds. Crop growth rate during each phenological phase, leaf blade growth rate during vegetative stage, stem growth rate during reproductive stage and panicle growth rate during ripening stage were higher in hybrids than in inbreds. The higher grain yield potential of indica/indica hybrids compared with indica inbreds was attributed to greater biomass production (Peng et al., 1999). The same observation was reported in “super” hybrid rice (Zong et al., 2000; Zhang et al., 2009). It had more biomass relative to ordinary hybrid and inbred varieties.

The morphological traits of “super” hybrid rice were moderate tillering capacity and heavy but drooping panicles at maturity (Yuan, 2001).

The high demands for ligno-cellulosic biomass for the production of bio-fuels provide value to vegetative biomass (Salas-Fernandez et al., 2009). The viability and profitability of high biomass crops depend critically on high outputs of biomass energy at low inputs of money and fossil fuels (Heaton et al., 2004). Rice is not a dedicated bio-energy crop but it can produce large amount of straw for ligno-cellulosic digestion. Being a model monocot species, rice can be a reference crop to understand genetics of important traits for bio-energy crops.

2.4 Rice Biomass Production and Drought

Drought is a major stress factor affecting crop production systems, especially in East Africa, South Asia and Australia and it is one of the major constraints causing yield loss in rice. About one third of world’s rice area is rainfed and these are all drought prone (David, 1991; Maclean et al., 2002) and it was estimated that around 50% of the world rice production areas is affected by drought (Bouman et al., 2005). Rice is a water loving plant so it is extremely susceptible to water stress. Aside to yield losses, drought increases the possibility of disease and insect attack on rice.

Rice can experience soil drought in several different growth stages (Price and Courtois, 1999) and the response of rice genotypes to this stress varies depending on the characteristics of drought stress environment. Various responses of rice plants to drought include reduced production of new tillers and leaves, reduced leaf elongation, rolling of existing leaves and promotion of leaf death (Culter et al., 1980; O’Toole and Cruz, 1980;

Hsiao et al., 1984; Turner et al., 1986). Young rice plants responded to drought at a lower soil water status than the older plants and the first effect of drought in the vegetative phase was a decline in leaf expansion phase compared to well watered plants (Wopereis et al., 1996). In limited water at the vegetative stage, De Datta et al. (1975) reported significant decrease in tiller number but it appeared least detrimental to yield. Drought stress at panicle development to anthesis stage was found highly critical since it can severely affect grain yield of rice (Matsushima, 1970; Cruz and O'Toole, 1984). Drought at anthesis leads to very high sterility of florets and hence lowering the percentage of filled grains (Boonjung and Fukai, 1996). In most cases, drought delayed flowering in rice (Bernier et al., 2007; Venuprasad et al., 2007; Kumar et al., 2009). Under drought, Kumar et al. (2006) indicated that the contribution of dry matter partitioning from stem and leaf increased significantly under water stressed condition compared to well watered condition, thereby affecting grain yield. Atlin et al. (2008) reported that grain yield was found to be a function of biomass production and harvest index at the vegetative and reproductive stage, respectively.

In rice, many physio-morphological characters confer drought tolerance (Pantuwan et al., 2002b; Yue et al., 2008). These traits include root density at depth, leaf water potential, osmotic adjustment, leaf rolling, canopy temperature and delay in flowering time (Fukai and Cooper, 1995; Garrity and O'Toole, 1995; Pantuwan et al., 2002a). Grain yield under stress was suggested to be a desirable direct trait for selection in drought prone environments (Ceccarelli et al., 1991). Fukai and Cooper (1995) reported that under drought condition, tolerant cultivars had higher production and yield stability than drought susceptible cultivars. Recently, Jongdee et al. (2002) suggested that leaf water potential, a major physiological trait associated with drought tolerance can be used to improve drought tolerance in rice.

The height of the rice plant is an important factor accounting for the above ground biomass. Plant height at vegetative stage is determined from the ground level to the tip of the tallest leaves, and for mature plants, it is measured from ground level to the tip of the tallest panicle. Kumar et al. (2009) reported that majority of the rice lines evaluated had reduction in plant height but the mean plant height reduction in drought tolerant lines was lower, ranging from 6-12 cm when compared to drought susceptible lines with higher height reduction ranging from 16-27 cm. Lafitte et al. (2006) reported that on an average, drought stress reduced plant height by 12%. However, in few *japonica* lines, increases in height under the same stress were noted. In maize, the plant height was significantly reduced in the early drought treatment as compared to the fully watered plots, and the plant height and biomass were significantly reduced up to 40% in two severe drought treatments (Asch et al., 2001).

It was also found that the leaf elongation rate of plant under stress in the vegetative phase decrease rapidly after an initial period of normal growth. Bradford and Hsiao (1982) reported that restriction of leaf growth was the first response to water deficit due to the high sensitivity of foliar expansion to water stress. Soil moisture depletion suppresses leaf expansion and midday photosynthesis (Kramer and Boyer, 1995). This effect of drought was also observed in pasture grasses (Turner and Begg, 1976; Sanderson et al., 1997).

Drought can greatly reduce biomass production in rice. Rice response to drought stress such as reduction in height, leaf area and biomass production, tiller abortion, changes in root dry matter and rooting depth, and delay in reproductive development will result in the reduction of total biomass yield (Asch et al., 2005). Considering the relation between leaf area and biomass production, Greco and Cavagnaro (2002) reported that water stress influenced final leaf area or on the rate at which leaf area is developed, and the leaf area, leaf blade dry matter and total aerial biomass were significantly reduced due to water stress. Bernier et al. (2009a) observed that under stress condition, both biomass yield and harvest index were severely reduced with a slight delay in flowering, and the highest reduction in the total plant biomass was up to 35%. Hsiao and Acevedo (1974) stated that the water status of plant influences the total plant biomass as well as the dry matter partitioning. Suralta and Yamauchi (2008) reported that in UPLRi7, NSICRc9, PSBRc82 and IR73888-1-2-7 rice genotypes studied, drought condition had a tendency to decrease shoot dry matter with PSBRc82 and IR73888-1-2-7 showing significant reduction of 70-79%. In a very recent drought study, Wang et al. (2009) found that the dry weight of shoot in rice cultivar IR62266 was reduced by 43%.

The growth and development of roots are very important in the adaptation of rice to soil water deficit (O'Toole, 1982; Fukai and Cooper, 1995; Price and Courtois, 1999; Price et al., 2002a; Wade et al., 1999a, 2000; Kato et al., 2006; Wang and Yamauchi, 2006). The deep and extensive root systems of rice in drought conditions help in accessing water at soil depth (O'Toole, 1982; Kondo et al., 2003). The root system of drought tolerant genotype can penetrate the hard pan which helps in drought adaptation (O'Toole, 1982; Fukai and Cooper, 1995; Wade et al., 1999a). In field grown rice, drying the soils can increase total root mass (O'Toole, 1982; Ingram et al., 1994) or the rooting depth (Mambani and Lal, 1983) but in controlled chamber experiment, there was a reduction of root growth under drought (Yamauchi et al., 1996). In some rice varieties, root morphological characteristics were known to be important in drought tolerance. Yoshida and Hasegawa (1982) reported that the deep rooting rice cultivars were more drought tolerant than those with shallow roots. Kondo et al. (2003) showed that the root distribution in relation to depth was closely related to drought tolerance. The rice roots from the top soil layer may decrease the water uptake rate with decreasing soil water potential but this can be compensated by roots at greater depth even if the soil water potential at that depth is also decreasing. Bernier et al. (2009a) concluded that deep rooting length and maximum rooting depth were the two most important traits positively correlated with water consumption in drought stress treatment. At constant 10% soil moisture content, considered as severe drought situation, there was a 95% reduction in root biomass of all cultivars evaluated (Jensen et al., 1998). Asch et al. (2005) observed that there was less severe reduction in root biomass at 14% soil moisture content and more root biomass was found in deeper soil level. At 25 DAS rice, plant height and tillering decreased significantly at 10-14% constant moisture content as compared to fully water controls and lowest R:S ratios were observed in the two most severe drought treatments (Asch et al., 2005).

Efforts have been made to improve the drought tolerance of rice and increase the yields in areas prone to drought. This includes the development of drought resistant varieties through direct selection for yield under stress and indirect selection for physio-morphological traits (Fukai et al., 1999; Fischer et al., 2004). However, limited success have been reported due to complexity of genetics and physiology underlying this trait (Li and Xu, 2007), low heritability and lack of effective screening criteria (Ouk et al., 2006). IRRI conducted the initial step of a large scale backcross breeding efforts to improve drought tolerance in rice (Lafitte et al., 2006). Several varieties were reported as drought tolerant such as TKM-1 (Mali and Mehta, 1977), Nootripathu, an indica landrace adapted to rainfed condition, (Babu et al., 2001), and Apo (IR55423-01), an improved indica upland variety with high-yield potential under aerobic soil condition (George et al., 2002). Recent efforts have been put to understand the genetics of drought adaptive traits in some of these varieties but it has been difficult to identify the genetic segments that influence the yield under stress (Babu et al., 2003). Several studies provide information on QTLs linked to drought related traits, grain yield and yield components under drought condition and these were summarized by Li and Xu (2007). Most of the QTLs had smaller effects but recent studies reported several QTLs with large effect. Bernier et al. (2007) identified a QTL (*qtl12.1*) on chromosome 12 explaining about 51% of the genetic variance for yield under severe upland drought stress over two years in the Vandana/Way Rarem population. Surprisingly, the allele conferring improved drought tolerance was contributed by Way Rarem, the less tolerant parent. A very recent study conducted on this QTL in wider range of environments, stress intensities and stress timing, indicated that the effect of this QTL on grain yield increased with increasing intensity of drought stress, confirming the large and consistent effect on grain yield (Bernier et al., 2009b). Mapping study of Venuprasad et al. (2009a) on Apo variety detected QTLs on chromosomes 2 and 3 with large effects on grain yield in both lowland drought and aerobic environments. The QTL in chromosome 3 near RM416 (DTY3.1) had a large effect on grain yield explaining about 31% of genetic variance and these effects have been observed in several other rice mapping populations. About 13-16% of the variation on grain yield in lowland drought stress was attributed to the second QTL (in chromosome 2) linked to RM324 (DTY2.1). Kumar et al. (2007) reported another major QTL for grain yield under lowland drought stress. It was from CT9993/IR62266 population and located on chromosome 1 explaining 32% of the genetic variance for the trait. In a very recent study, Gomez et al. (2010) reported several QTLs for drought and some QTLs can explain 32% of the variations in IR20 and Nootripathu cross. QTLs that were consistent across genetic backgrounds and trials were also reported. Venuprasad et al. (2009b) identified similar regions such as loci RM572 and RM6703 on chromosome 1, RM520 on chromosome 3, RM256 on chromosome 8, RM269 on chromosome 10, and RM511 on chromosome 12 that had consistent effects on grain yield under drought stress in the Apo/IR64 populations and three of these (RM6703, RM520, and RM511) were found also in other populations. Similarly, Gomez et al. (2010) reported a common segment such as genomic segments RM212-RM302 on chromosome 1, marker I12S on chromosome 4 and RM240 on chromosome 2 that can be useful for near-isogenic development needed in the genetic dissection of drought tolerance in rice.

2.5 Rice Biomass Production in Rainfed and Flooded Conditions

Rice can be grown in rainfed and flooded fields although the most popular is growing in flooded fields. Non-flooded (dry land) areas included the rainfed areas, non-flooded lowland and upland rice fields. During rainy months, rainfed areas are flooded and maybe fully submerged. Flooded conditions may impact the production of biomass and grain yield. It was reported that water logging, common in flooded conditions significantly decreased the number of tillers (Suralta and Yamauchi, 2008). Hayashi et al. (2006) reported that the two cultivars studied had high tillering ability under flooded conditions. In China, Shi et al. (2002) concluded that in treatments with soil water tables 5 cm above and below the soil surface, rice produced almost the same total above ground biomass, whereas the root biomass production in the treatment where soil water table was 5 cm below the soil surface was higher. In treatments where the soil water tables were 20 and 40 cm below the soil surface, the root production was more concentrated in the upper 5 cm below the soil surface (Shi et al., 2002).

Water deficiency that may occur in non-flooded soil can induce reduction in water potential and this may result to leaf rolling (O'Toole and Cruz, 1980) or reduction in photosynthetic rate (Ishihara and Saito, 1987). Granier and Tardieu (1999) showed that the water deficiency reduced leaf relative expansion and cell division rates that led to decreased leaf area. Response of rice to rainfed condition included delay in flowering and high percentage of sterility, leading to low grain yield. The yield and plant height, and yield and maturity had inconsistent correlation in the experiment conducted by Lafitte et al. (2007) and the correlation between maturity and plant height were consistently negative. Non-flooded soil called aerobic soil reduced plant biomass of both wild type and mutant rice evaluated, however, the two mutants studied produced up to 44% more shoot biomass and up to 4 fold more root dry matter than the wild type under aerobic conditions (Cairns et al., 2009). In rainfed lowland, roots are shallow and it is unclear whether the crop has sufficient roots at depth to extract water as drought progresses (Wade et al., 1999b). Shi et al. (2002) concluded that in rice plants that were grown under intermittent irrigation had higher root activities, produced more tiller $hill^{-1}$ and biomass and their leaves had higher chlorophyll content.

Under flooded conditions, rice plants grew taller, produced bigger tillers and maintained superiority until maturity over those grown under non-flooded conditions (Chaudhry and McLean, 1963) and much recent study support these findings. Kamoshita and Abe (2007) showed that the number of tillers and above ground biomass were reduced in non-flooded trial than the flooded trial. At the heading time, the tiller number, leaf area index and above ground biomass in non-flooded trial were about 70% of the flooded. Moreover, the plant height was reduced in non-flooded trial than flooded trial. Cairns et al. (2009) observed that in flooded conditions, there were no significant phenotypic differences between the wild type and the mutant studied but non-flooded stress reduced shoot and root traits but not plant height. It was also noted that were no significant differences in total root volume and dry weight between mutant and wild type under drought stress. The shoot dry matter of a cultivar at heading in flooded field was significantly greater than that in non-flooded (Hayashi et al., 2006). At maturity, the root length and root mass were smaller in non-flooded trial as compared to the flooded trial whereas the rooting depth index did not change (Kamoshita and Abe, 2007). More above ground total biomass was produced by flooded rice as compared to aerobic rice but the differences became significant in the third season and the differences between above ground total biomass between aerobic and flooded rice gradually widened as the number of cropping seasons increased (Peng et al., 2006). In a three year experiment, Bouman et al. (2005) concluded that less biomass was accumulated under aerobic conditions than under flooded conditions and reduced leaf area development; reduced biomass growth and reduced yield were some of the effects of water stress.

Intermittent flooding or staggered water application typical in rainfed areas was found beneficial in saving water and increasing grain yield than in fully irrigated field. Intermittent irrigation produced up to 36% more tillers compared to flooded irrigation (Gani et al., 2002). It was reported that intermittent irrigation consistently produced more tillers and taller plants, larger leaf area and higher biomass compared to continuously flooding. The same response was reported by Shi et al. (2002). Their results showed that the number of tillers hill^{-1} in the three cultivars studied was higher in intermittent irrigation and dry cultivation than in flooded treatment.

CHAPTER III

MATERIALS AND METHODS

3.1 Source of Test Entries

The materials for evaluation were obtained from high biomass rice breeding project of Texas AgriLife Research and Extension Center, Beaumont, Texas which was aimed to develop high biomass rice that would be useful in studying biomass production for a dedicated bioenergy feedstock. These breeding lines were generally late maturing, with large tiller or with many tillers, leafy and taller than conventional rice. These were derived from breeding populations developed for breeding high grain yield thus these were undesirable for high grain yield but has potential for high biomass production.

3.2 Experiment 1: Response of Selected High Biomass Rice to Different Percentages of Field Capacity

Ten selected genotypes that were good performers in the high biomass field trials conducted in 2008 were used in pot experiments aimed to evaluate biomass production in water-limited environment. Table 1 shows the pedigree of the selected high biomass rice.

Table 1. Selected high biomass rice genotypes and their pedigrees.

Genotype	Pedigree
4	LQ 243a/Francis
5	Cocodrie/LQ275a
6	Cocodrie/LQ275a
7	Cypress/L201
10	Cypress/SABR
11	L201/ZHE733
12	Unknown
14	CocodrieLQ158
16	Cypress/LQ158
20	Banks

Five seeds of each genotype were seeded in 16 cm diameter plastic pot with equal amount of dry League soil type and arranged in a completely randomized design with three replications. Equal amount of water was used until germination. At 20 days after sowing (DAS), thinning to one plant was done and the following treatments were used;

1. 50% FC
2. 75% FC
3. 100% FC

These water levels were maintained throughout the experiment by weighing the pots every other day while the evaporated water was compensated by adding extra water. One extra pot without plant for 75% and 50% FC was maintained and the water evaporated from those pots was used to add water in the experimental pots at the same FC. Nitrogen fertilizer was applied in two splits; first at planting at the rate of 57 kg ha^{-1} and second at tillering at the rate of 91.2 kg ha^{-1}. The final data gathering was done 85 DAS.

The first data collected was the date of first tiller emergence, the date when the first tiller with one fully expanded leaf appeared at the base of the plant. Daily observations were made to note this date. Weekly tiller and leaf count were gathered by counting the tillers including the newly emerged tillers with one fully expanded leaf and counting the leaves including those at least half emerged and expanded. Weekly plant height was also gathered by measuring the length of the plant from soil surface to the tip of the longest leaf. The shoot and root weights were collected by weighing the upper part of the plant and root including the node where the upper most roots originated after carefully removing soil at the end of the experiment (85 DAS). These samples were air dried for 30 days to obtain the shoot and root dry weights. Rate of tiller production, rate of leaf production and rate of increase in plant height were computed by finding the slope of number of tillers and leaves, and plant height at weekly intervals. Fresh and dry R:S ratio was obtained by dividing the root fresh weight (FW) by shoot FW and root dry weight (DW) by shoot DW, respectively. Percent dry matter (% DM) was derived by dividing the biomass dry weight by the total fresh biomass weight and multiplying by 100.

3.3 Experiment 2: Response of Selected High Biomass Rice to Rainfed and Flooded Conditions

This experiment was conducted in the field of Texas AgriLife Research and Extension Center at Beaumont, Texas (30.06˚N, 94.29˚W). Twenty selected genotypes that performed good in the high biomass trials conducted in the field in 2008 were field planted to evaluate their biomass production in rainfed and flooded environment. Table 2 shows the pedigree of the selected high biomass rice.

Table 2. Selected high biomass rice genotypes for field trials and their pedigrees.

Genotype	Pedigree
1	LQ243a/Saber//L201
2	LQ243a/L201//RU0301081
3	LQ243a/Francis
4	LQ243a/Francis
5	Cocodrie/LQ275a
6	Cocodrie/LQ275a
7	Cypress/L201
8	Cypress/LQ158
9	Cypress/LQ158
10	Cypress/Saber
11	L201/ZHE733
12	Unknown
13	Cocodrie/WELLS
14	Cocodrie/LQ158
15	Cocodrie/LQ275a
16	Cypress/LQ158
17	Cypress/9901081
18	Cocodrie/L202
19	Cocodrie/ZHE733
20	Banks

The experiment was established in League clay soil common at the Beaumont Center. The soil was prepared using disc harrow and rotavator to pulverize the soil, and was laser leveled. Before planting, levees were made to facilitate water control. At the time of planting, 57 kg ha^{-1} urea was applied. Second application of urea was done at flooding at the rate of 91 kg ha^{-1} and the last application was at panicle differentiation at the rate of 80 kg ha^{-1}. The P_2O_5 fertilizer was applied at planting at the rate of 34 kg ha^{-1}.

A split-plot design with two replications was used, with the flooded and rainfed environments as the main plot, and high biomass rice genotype as sub-plot. Each sub-plot had three rows that were 3 m long and 25 cm apart. Seeds were sown using a planter at the rate of 2-3 grams row^{-1}. Three herbicides were used to control the weeds prevalent in the area namely Command at the rate of 1.2 l ha^{-1} and Permit and Aim at the rate of 70 g ha^{-1} applied at the 2-7 leaf stage. Insecticide Karate at the rate of 140 g ha^{-1} was applied to control insects. The flooded treatment had permanent flood starting from 30 days after seedling emergence while rainfed treatment was flush flooded when rainwater was not enough to avoid soil cracking and wilting of the plants. The rainfall received during emergence to harvest was 11.57 inches.

The data collected were tiller counts from 750 cm^2 row starting at eight weeks after sowing and repeated every two weeks until majority of the entries reached flowering stage. Flowering date was gathered when 50% of the panicles of plants in a plot had opened florets. The plant height at maturity was measured from the soil level to the tip of the tallest panicle. The total weight of above ground biomass of all the plants in a plot at maturity was gathered along with the date at which the crop was harvested. The rate of increase in tillers/750 cm^2 was computed by finding the slope of number of tillers/750 cm^2 at bi-weekly intervals and number of tillers plant^{-1} at 105 DAS was computed by dividing the total number of tillers/750 cm^2 by number of plants/750 cm^2.

3.4 Statistical Analysis

All the data gathered were statistically analyzed using analysis of variance (ANOVA; SAS software). The means were separated using Duncan's t test at an alpha level of 0.05.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Experiment 1: Response of Selected High Biomass Rice to Different Percentages of Field Capacity

The changes in water balance equation that produce internal water stress in plants result in agricultural drought. Reduction in germination percentage and thus reduction in plant stands; reduced tillering and plant growth rates which will finally lead to diminished quantity and quality of harvested products are some of the influential effects of drought (Nix, 1982). These effects are more extreme during water stress at critical stages of crop development. Response of rice to drought has been studied extensively as a food crop but limited experiments had been made to study the response of rice as crop for biomass production in drought stress condition. One of the objectives in this thesis was to study the variation among selected high biomass rice lines under drought conditions.

4.1.1 Tillering related traits

4.1.1.1 *Days to first tiller emergence*

The ten genotypes had variation in the number of days at which the first tiller with fully expanded leaf appeared at the base of the plant. The analysis of variance showed that the differences in the number of days to first tiller in three levels of FC and in genotypes were significantly different whereas the interaction between % FC and genotype was not significant (Table 3). The emergence of first tiller across all ten genotypes was first observed in 100% FC. It took only 36.67 days to produce the first tiller (Table 4). As expected, drought conditions delayed formation and appearance of tillers. At 75% FC, emergence of first tiller was delayed by 4.65 days (41.32 DAS) and at 50% FC it was delayed by 8.92 days (45.59 DAS). The appearance of the first tiller among genotypes across the three FCs (drought levels) ranged from 36.11-46.14 DAS (Table 5) with a mean of 41.26. The fastest genotype to produce the first tiller was genotype 12 and the last to produce its first tiller was the conventional rice check cultivar 'Banks'. Four genotypes produced the first tiller similar with Banks. The first (genotype 12) and last (genotype 16) genotypes to produce the first tiller were significantly different from each other ($p \leq 0.01$). The earliest to produce first tillers (genotype 12) was statistically similar with the other two high biomass genotypes evaluated (genotype 10 and 11). The difference between the earliest and latest genotypes to produce the first tiller was 10 days and all high biomass genotypes except one had the first tiller at least 3 days earlier than Banks.

Table 3. Mean squares of the ANOVA showing the effects of percentage field capacity, genotypes and their interaction on the days to first tiller emergence, number of tillers and rate of tiller production at Beaumont, Texas in summer 2009.

Source	df	Days to first tiller emergence		Number of tillers				Rate of tiller production	
				43 DAS[¶]		85 DAS			
		MS	Prob > F	MS	Prob > F	MS	Prob > F	MS	Prob > F
Genotype (G)	9	93.62	**	12.36	**	88.18	**	0.0191	**
FC[†]	2	605.61	**	23.90	**	7.05	NS	0.0126	**
G x FC	18	12.96	NS[‡]	0.37	NS	2.72	NS	0.0014	NS

**Significance at $p \leq 0.01$.
[¶]DAS, days after sowing.
[†]FC, field capacity.
[‡]NS, non-significant.

Table 4. Means of days to first tiller emergence, number of tillers and rate of tiller production in three percentages of field capacity across ten genotypes at Beaumont, Texas in summer 2009.

% Field Capacity	Days to first tiller emergence	Number of tillers		Rate of tiller production
		43 DAS[¶]	85 DAS	
50	45.59a	1.17c	5.79	0.1117a
75	41.32b	1.79b	5.89	0.0785b
100	36.67c	2.90a	6.57	0.0731b

Means with the same letters are not significantly different at 5% level of significance.
[¶]DAS, days after sowing.

Table 5. Means of the days to first tiller emergence, number of tillers and rate of tiller production across drought levels of nine high biomass rice and cultivar Banks at Beaumont, Texas in summer 2009.

Genotype	Days to first tiller emergence	Number of tillers		Rate of tiller production
		43 DAS¶	85 DAS	
4	42.56abc	1.11cd	3.22d	0.0408e
5	42.88abc	1.00cd	4.13cd	0.0605de
6	41.33bc	1.67bc	3.78d	0.0419e
7	40.67cd	1.89bc	5.78c	0.0941cd
10	38.89cde	2.67b	8.22b	0.1247bc
11	36.89de	4.00a	11.78a	0.1757a
12	36.11e	3.78a	10.89a	0.1439ab
14	42.00abc	1.44cd	4.67cd	0.0623de
16	45.22ab	1.22cd	4.33cd	0.0674de
Banks	46.14a	0.43d	3.29d	0.0553de
Means	41.26	1.92	6.01	0.0866
CV%	9.49	56.91	27.98	25.10

Means with the same letters are not significantly different at 5% level of significance.
¶DAS, days after sowing.

All genotypes had similar response pattern in three levels of FC. Drought stress delayed the emergence of first tiller for all genotypes (Table 6). However, the earliest genotype (genotype 11) was least affected. It had only 2-3 days delay whereas most of the genotypes had seven days or more to have its first tiller. Early tillering can be beneficial in suppressing weeds that could be critical in early growth and development of rice and in the production of large amount of biomass. The early tillering ability of genotype 11 may have originated from the parent cultivar ‘Zhe733’, a Chinese cultivar known to produce tillers earlier than conventional U.S. rice varieties (Tabien et al., 2005).

Table 6. Variations in days to first tiller emergence, number of tillers and rate of tiller production among selected high biomass rice at three levels of field capacity at Beaumont, Texas in summer 2009.

Genotype	Days to first tiller emergence			Number of tillers 43 DAS[¶]			Number of tillers 85 DAS			Rate of tiller production		
	100	75	50	100	75	50	100	75	50	100	75	50
4	37.67	41.33	48.67	2.33	1.00	0.00	3.67	3.33	2.67	0.70	0.64	0.42
5	38.33	43.00	47.33	2.00	1.00	0.00	5.00	3.50	3.67	0.95	0.68	0.66
6	37.67	39.00	47.33	2.33	2.00	0.67	4.67	3.00	3.67	0.88	0.60	0.64
7	36.33	40.67	45.00	2.67	1.67	1.33	5.67	6.00	5.67	1.09	1.15	0.88
10	33.00	40.00	43.67	4.00	2.67	1.33	10.00	7.33	7.33	1.87	1.39	1.23
11	35.00	38.00	37.67	5.00	3.33	3.67	11.67	10.67	13.00	2.13	1.88	1.93
12	29.00	40.00	39.33	4.67	3.67	3.00	9.67	12.00	11.00	1.76	2.10	1.69
14	37.33	43.33	45.33	2.67	1.00	0.67	6.33	4.33	3.33	1.22	0.83	0.60
16	39.33	43.67	52.67	2.33	0.67	0.67	5.67	4.00	3.33	1.09	0.75	0.57
Banks	43.00	46.50	50.50	1.00	0.00	0.00	3.33	3.00	3.50	0.65	0.56	0.61

[¶]DAS, days after sowing.

4.1.1.2 *Number of tillers at 43 DAS and 85 DAS*

The analysis of variance shows that the variations in tiller count at 43 DAS in three levels of FC and variations in number of tillers at 43 and 85 DAS in genotypes were highly significant whereas number of tillers at 85 DAS in three levels of FC and interaction between % FC and genotype, number of tillers at 43 and 85 DAS were not significant (Table 3). At 43 DAS, 100% FC had highest number of tillers (2.90) followed by 75% FC (1.79) and 50% FC (1.17) and these were statistically different from one another (Table 4). The tiller number at 85 DAS although statistically the same was following the trend as that on 43 DAS. The number of tillers among the genotypes across various FCs had an average of 1.92 tillers on 43 DAS and 6.00 tillers at 85 DAS. The highest number of tillers plant^{-1} was obtained in genotype 11 at both 43 DAS (4.00 tillers) and 85 DAS (11.78 tillers) and it was comparable to the tiller count of genotype 12 at both stages (Table 5). The lowest number of tillers was counted from Banks (0.43

tillers) at 43 DAS and from genotype 4 (3.22 tillers) at 85 DAS. Although genotype 4 had the lowest tiller count at the end of the experiment, it was comparable to four high biomass genotypes and Banks. At early tillering stage, four high biomass rice genotypes had comparable tiller number to Banks but this number of comparable genotypes increased to five past maximum tiller. In both stages, four genotypes were consistently higher in tiller count than Banks.

The number of tillers in all genotypes was severely affected by drought. Lowest number of tillers was always obtained at 50% FC. Two genotypes (genotype 11 and 12) seem less affected by drought at older stage. These genotypes performed well at 85 DAS, with 1.33 more tiller at 50% FC than 100 % FC. Like conventional rice, the development of tiller of high biomass was affected by drought. Lack of enough water reduced tiller count. Similar reduction in tiller number due to drought stress was seen in other genotypes (De Datta et al., 1975; Matsuo et al., 2007; Suralta and Yamauchi, 2008). The high number of tillers and faster tiller production can be attributed to faster node production. Reports indicated that genotypes that produced more tillers had fast node production rate (Wu et al., 1998; Samonte et al., 2006). During early selection for high biomass rice, tillering ability was one of the main traits for consideration in the generation advancement. Report indicated that tillering ability was moderately heritable (Tabien et al., 2005), thus early selection is feasible as shown.

4.1.1.3 *Rate of tiller production*

The difference in rates at which tillers were produced was also significant in the three levels of FC, and in genotypes as shown in the analysis of variance whereas the interaction between % FC and genotype was not significant (Table 3). The rate of tiller production was fastest at 100% FC and slowest at 50% FC. The rate of tiller production at 100% and 75% was significantly different from 50% FC (Table 4). The imposed drought reduced tiller count by 1.11-1.73 tillers plant^{-1} and the rate of tiller production varied from 0.04-0.17. Among the genotypes, the fastest rate of tiller production was obtained by genotype 11 and slowest rate was obtained by genotype 4 (Table 5, Figure 1). Genotype 4, 5, 6, 14 and 16 produced tillers at a similar rate as the check, Banks. The fast tillering genotypes, (11 and 12) had 3.31 times more tillers than Banks. Except for genotype 1, all high biomass selections had numerically more tillers than Banks and faster in tiller production.

The rate of tiller production of all genotypes was also severely affected by drought. Slowest rate of tiller production was always obtained at 50% FC. Genotype 12 seems to be better in tiller production than genotype 11 but the two were the fastest in tiller production among the genotypes evaluated. Severity of drought affects apical development that can delay tiller emergence and tiller development. Severe water deficit suspend apical development while mild water deficit reduces the rate of apical development (Lilley and Fukai, 1994a). The reduction in tiller production under water stress could also be attributed to limited assimilates produced from inhibited photosynthesis directly caused by drought (Mostajeran and Rahimi-Eichi, 2009).

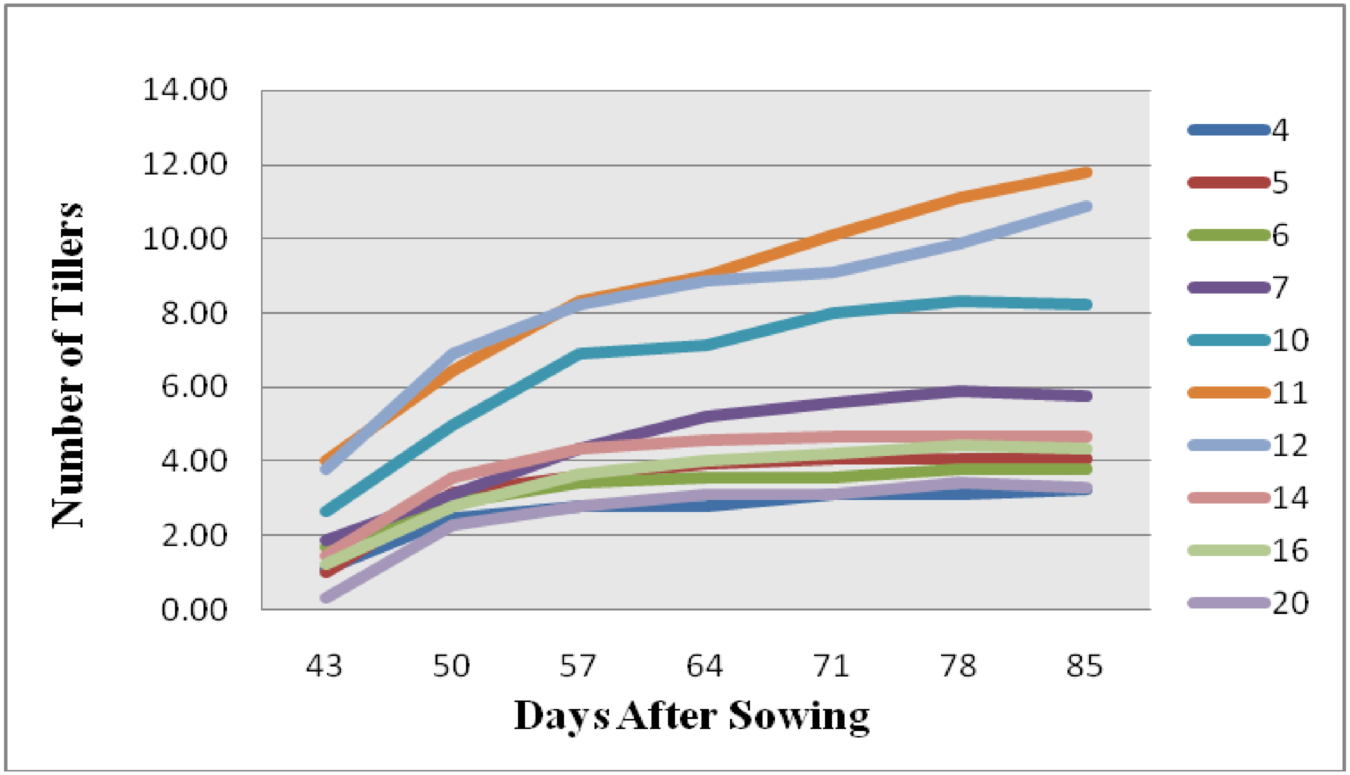

Figure 1. The rate of tiller production of ten genotypes across three field capacities.

4.1.2 Leaves related traits

4.1.2.1 *Number of leaves at 43 and 85 DAS*

The variations in the number of leaves at 43 and 85 DAS in three different levels of FC, 10 genotypes and the genotype x FC interaction (Table 7) were not statistically different, indicating that these traits were not affected by water stress and genotype. However, numerical differences were noted and the trend was the reverse of tillering traits, the highest number of leaves at 43 DAS was counted at 50% FC followed by 75% and 100% FC (Table 8). At 85 DAS, 75% FC had highest number of leaves and 100% FC had lowest number of leaves. Numerically, genotype 6 and 14 had highest number of leaves (6.33) at 43 DAS and genotype 4 had most leaves (13.78) at 85 DAS (Table 9). The lowest number of leaves was obtained from genotype 16 at 43 DAS and in genotype 11 at 85 DAS. The ten genotypes tend to produce more leaves in drought conditions than at 100% FC, although it was statistically the same. It can be noted that leaf number in genotype 11 and 12 were least affected in stress condition (50% FC) (Table 10). The numerically higher leaf count at 50% FC can be related to possible early shift to flowering stage. Plants exposed to stress condition can activate the flowering program prematurely. This stress activated flowering which enhances the chance of the population to survive in threatening environmental condition. None of the genotypes were flowering at the end of the experiment. Date of flowering could have been a good parameter to indicate if there was a faster shift to reproductive stage. Variation in leaf number among genotypes in very diverse germplasm was noted in Zhe 733, Cypress and

Cocodrie (Tabien et al., 2005). The similarities in leaf number among genotypes can be due to limited number of genotypes evaluated and some similarities based on pedigrees.

Table 7. Mean squares of the ANOVA showing the effects of percentage field capacity, genotypes and their interaction on the number of leaves and rate of increase in leaves at Beaumont, Texas in summer 2009.

Source	df	Number of leaves				Rate of increase in number of leaves	
		43 DAS¶		85 DAS			
		MS	Prob > F	MS	Prob > F	MS	Prob > F
Genotype (G)	9	0.22	NS‡	8.69	NS	0.0029	NS
FC†	2	2.81	NS	6.51	NS	0.0030	NS
G x FC	18	1.02	NS	7.55	NS	0.0021	NS

¶DAS, days after sowing.
†FC, field capacity.
‡NS, non-significant.

Table 8. Means of number of leaves and rate of increase in number of leaves in three percentages of field capacity across ten genotypes at Beaumont, Texas in summer 2009.

% Field Capacity	Number of leaves		Rate of increase in number of leaves
	43 DAS¶	85 DAS	
50	6.48	11.79	0.1212
75	6.11	12.04	0.1361
100	5.87	11.10	0.1158

¶DAS, days after sowing.

4.1.2.2 *Rate of increase in number of leaves*

The variations in the rate of increase in number of leaves of the main tiller in three different levels of FC, in 10 genotypes and genotype x FC interaction (Table 7) were not statistically different. The fastest increase in leaves was observed at 75% FC and the lowest was at 100% FC (Table 8). The rate at which the number of leaves increased ranged from 0.099-0.1632 (Table 9). The ten genotypes tend to produce faster leaves in drought conditions than at 100% FC, although it was statistically the same (Figure 2). Rate of leaf production in genotype 11 and 12 were least affected in stress

Table 9. Means of number of leaves and rate of increase in number of leaves across drought levels of nine high biomass rice and cultivar Banks at Beaumont, Texas in summer 2009.

Genotype	Number of leaves		Rate of increase in number of leaves
	43 DAS[¶]	85 DAS	
4	6.11	13.78	0.1632
5	6.25	11.13	0.1103
6	6.33	12.44	0.1383
7	6.11	11.00	0.1139
10	6.00	11.11	0.1156
11	6.00	10.22	0.0992
12	6.22	11.44	0.1133
14	6.33	11.78	0.1241
16	5.89	11.22	0.1252
Banks	6.29	12.30	0.1399
Means	6.15	11.64	0.1243
CV%	16.54	22.48	23.22

[¶]DAS, days after sowing.

Table 10. Variations in number of leaves and rate of increase in number of leaves among selected high biomass rice at three levels of field capacity at Beaumont, Texas in summer 2009.

Genotype	Number of leaves						Rate of increase in number of leaves		
	43 DAS[¶]			85 DAS					
	100	75	50	100	75	50	100	75	50
4	5.67	6.00	6.67	12.00	12.67	16.67	2.17	2.19	2.97
5	5.33	6.00	7.33	10.67	10.50	12.00	1.91	1.88	2.14
6	6.00	6.00	7.00	11.33	15.00	11.00	1.99	2.71	1.99
7	6.00	5.33	7.00	10.00	11.33	11.67	1.84	2.07	2.10
10	6.33	6.00	5.67	13.00	10.33	10.00	2.40	1.87	1.75
11	5.33	7.00	5.67	8.33	12.67	9.67	1.57	2.33	1.77
12	6.33	6.67	5.67	10.67	13.00	10.67	1.87	2.45	1.89
14	6.00	6.00	7.00	12.00	11.00	12.33	2.14	1.98	2.20
16	5.67	5.67	6.33	10.33	10.67	12.67	1.78	1.93	2.17
Banks	6.00	6.50	6.50	12.67	13.00	11.00	2.20	2.25	2.03

[¶]DAS, days after sowing.

condition (50% FC) as shown. Some variations in leaf size as affected by drought were observed but the rate of leaf production of the main tiller among genotypes showed small differences. Variations in rate of leaves production were noted in three diverse genotypes, Zhe 733, Cypress and Cocodrie (Tabien et al., 2005). Zhe733 produced faster leaves than the two U.S. varieties. The selected high biomass genotypes were all comparable to Banks, thus maybe similar to Cypress and Cocodrie, typical for conventional rice varieties in leaf production.

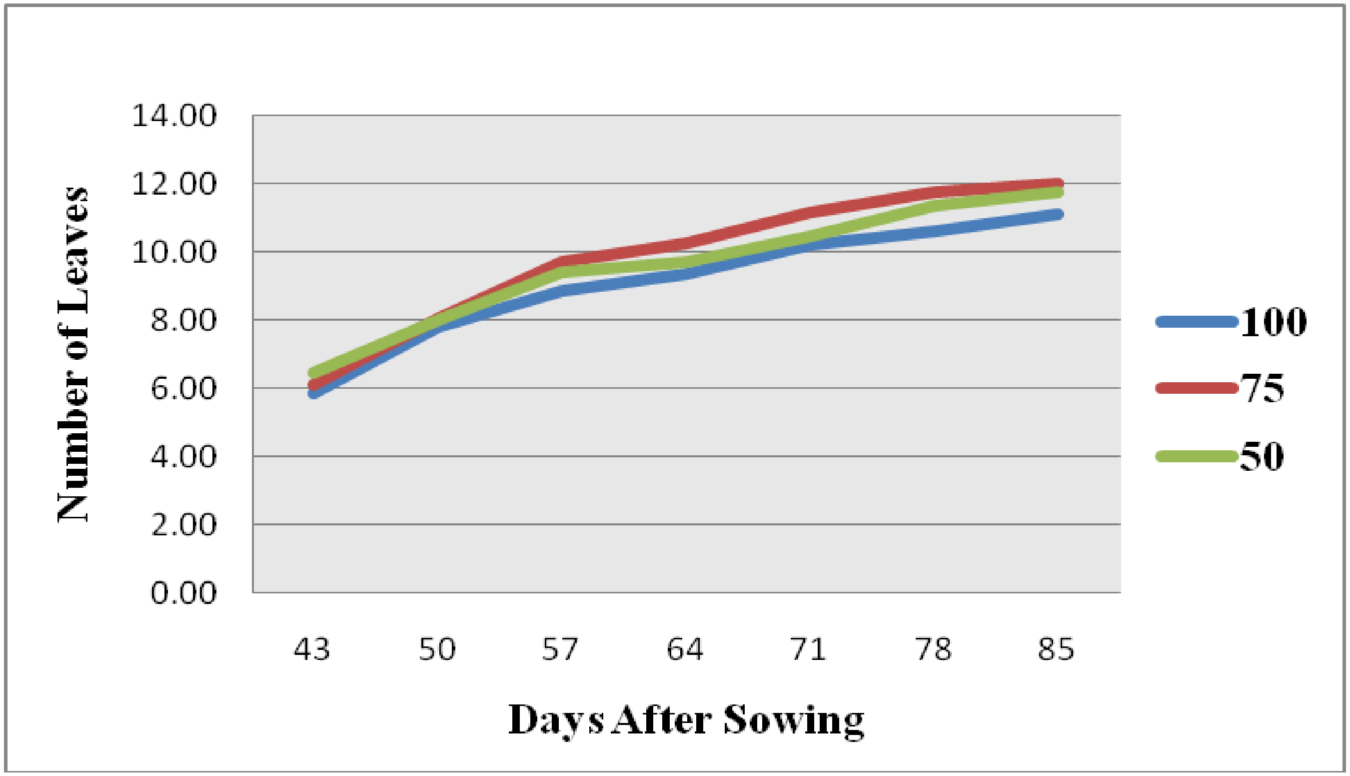

Figure 2. The rate of increase in number of leaves in three field capacities across ten genotypes.

4.1.3 Plant height

4.1.3.1 *Height at 43 and 85 DAS*

Plant height was affected by water stress. The results of the analysis of variance indicated that the plant heights at 43 DAS and 85 DAS in three levels of FCs, 10 genotypes and the genotype x FC interaction at 85 DAS were highly significant whereas the interaction on the plant height at 43 DAS was not significant (Table 11). The tallest plants were observed at 100% FC and shortest at 50% FC (Table 12). The plants at 100% FC were 61.03 cm tall at 43 DAS whereas 44.21 cm in 50% FC. Relative to 100% FC, the reduction in plant height at 43 and 85 DAS due to stress was 6.74-16.82 cm and, 6.64-24.65 cm, respectively. Limited water (50% FC) reduced height of the high biomass rice by 28-30% at 43 and 85 DAS. The mean height of the genotypes across the drought levels at 43 DAS ranged from 48.89-60.00 cm and at 85 DAS, it ranged from 62.72-79.44 cm with a mean of 72.60 cm (Table 13). Genotype 7 was the tallest genotype both at 43 DAS and 85 DAS with means 60.00 cm and 79.44 cm, respectively. The shortest genotypes at 43 DAS were genotype 11 and 14 which were similar to genotype 4, 12, 16 and Banks whereas at 85 DAS, genotype 12 was the shortest but it was comparable to genotype 4 and significantly shorter than the rest of the genotypes. Except the extremes (genotype 7 and 12), all the other genotypes were comparable to Banks. Genotype 7 (tallest) at 43 DAS and 85 DAS was 1.19 and 1.12 times taller than

Table 11. Mean squares of the ANOVA showing the effects of percentage field capacity, genotypes and their interaction on plant height and rate of increase in plant height at Beaumont, Texas in summer 2009.

Source	df	Plant height (cm)				Rate of increase in plant height	
		43 DAS[¶]		85 DAS			
		MS	Prob > F	MS	Prob > F	MS	Prob > F
Genotype (G)	9	152.69	**	202.59	**	0.0737	**
FC[†]	2	2127.56	**	4602.50	**	0.1939	**
G x FC	18	37.97	NS[‡]	103.51	**	0.0336	NS

**Significance at $p \leq 0.01$.
[¶]DAS, days after sowing.
[†]FC, field capacity.
[‡]NS, non-significant.

Table 12. Means of plant height and rate of increase in plant height in three percentages of field capacity across ten genotypes at Beaumont, Texas in summer 2009.

% Field Capacity	Plant height (cm)		Rate of increase in plant height
	43 DAS[¶]	85 DAS	
50	44.21c	57.62c	0.3044a
75	54.29b	75.59b	0.4518a
100	61.03a	82.27a	0.4564b

Means with the same letters are not significantly different at 5% level of significance.
[¶]DAS, days after sowing.

Banks. The ten genotypes tend to produce plants with shorter height at 43 DAS in drought conditions than at 100% FC, although it was statistically the same. The height of genotype 11 at 43 DAS was least reduced (21%) at 50% FC. The highest height reduction (50%) at 43 DAS was obtained in genotype 4 grown at 50% FC and the least was from genotype 6 with 14% at the same FC. At 85 DAS, the plant height varied from 42.33-92.83 cm. The mean of all the high biomass rice genotypes at all the three levels of FC was 71.88 cm (Table 14). Genotype 7 was the tallest at 100% FC but it was comparable to itself when grown at 75% FC. Genotypes 4, 5, 6, 10, 11 and 14 at 100% FC and genotypes 5, 6, and 7 at 75% FC were also comparable to genotype 7 at 100%

Table 13. Means of plant height and rate of increase in plant height across drought levels of nine high biomass rice and cultivar Banks at Beaumont, Texas in summer 2009.

Genotype	Plant height (cm)		Rate of increase in plant height
	43 DAS[¶]	85 DAS	
4	52.11cd	67.78bc	0.3160b
5	54.13bc	73.38ab	0.3721b
6	58.11ab	75.17ab	0.3704b
7	60.00a	79.44a	0.3894b
10	57.89ab	74.89ab	0.3653b
11	48.89d	74.50ab	0.6216a
12	50.33cd	62.72c	0.2942b
14	48.89d	69.56b	0.4569b
16	51.33cd	70.89b	0.4240b
Banks	50.29cd	70.79b	0.4398b
Means	53.19	71.91	0.4049
CV%	8.69	9.22	10.23

Means with the same letters are not significantly different at 5% level of significance.
[¶]DAS, days after sowing.

FC. The shortest height was obtained in genotype 4 at 50% FC and this was comparable to genotype 12 at the same FC. Banks at 100% FC was comparable to all the other genotypes except genotype 7 at same FC and genotype 4, 5, 6, 7, 10, 11 at 75% FC. Banks at 75% FC was as tall as genotypes 10, 11, 12, 14, and 16 at same FC and to all genotypes at 50% FC except genotype 4 and 12. Heights of Banks, genotype 14 and 16 at 100% FC were not comparable when grown at 75% FC, thus could be considered drought sensitive. The rest of the genotypes (group of 7) were less sensitive since these had comparable heights when grown at 100% and 75% FC. However, considering response at 75% and 50% FC, the group with Banks had comparable heights, thus less sensitive to further water stress. The other group had all significant differences between 75% and 50% FC, suggesting drought sensitivity at further water reduction (50% FC). Previous studies reported reduction in plant height among the genotypes as a result of drought (Asch et al., 2005; Lafitte et al., 2006). At 85 DAS, Matsuo et al. (2007) reported that drought decreased plant height by 25.57%. The reduction in plant height under water stress was shown to be associated with decline in cell enlargement and more leaf senescence (Bhatt and Srinivas Rao, 2005).

Table 14. Variations in plant height and rate of increase in plant height among selected high biomass rice at three levels of field capacity at Beaumont, Texas in summer 2009.

Genotype	Plant height (cm)						Rate of increase in plant height		
	43 DAS¶			85 DAS					
	100	75	50	100	75	50	100	75	50
4	64.33	53.00	39.00	82.17abc	78.83bcd	42.33j	0.36	0.51	0.08
5	65.67	53.50	43.00	82.00abc	84.50ab	57.33hi	0.34	0.59	0.26
6	59.67	64.33	50.33	80.00abcd	85.17ab	60.33ghi	0.41	0.46	0.25
7	68.00	62.00	50.00	92.83a	86.33ab	59.17ghi	0.50	0.47	0.20
10	65.00	60.67	48.00	84.50ab	78.17bcd	62.00fgh	0.43	0.36	0.29
11	55.67	47.00	44.00	86.00ab	76.17bcde	61.33fgh	0.73	0.70	0.43
12	58.00	52.67	40.33	71.83cdef	66.50efgh	49.83ij	0.33	0.33	0.23
14	59.67	44.67	42.33	82.00abc	66.00efgh	60.67ghi	0.55	0.42	0.40
16	60.00	50.33	43.67	81.33bc	69.17defg	62.17fgh	0.39	0.40	0.48
Banks	54.33	54.50	40.00	80.00bcd	64.25efgh	63.50fgh	0.53	0.25	0.49

Means with the same letters are not significantly different at 5% level of significance.
¶DAS, days after sowing.

The tallness of these genotypes can be due to the absence of *sd-1*, the common dwarfing gene in short (semi-dwarf) conventional rice. In particular, genotype 7 may have had the tallness gene from its parent L-201, known to have more erect and darker leaves and taller compared to other semi-dwarf cultivars (Tseng et al., 1979). These taller plants may have had more nodes as Samonte et al. (2006) have shown that taller plants had more nodes. However, considering the earlier similarities in leaf number, internode elongation could be the main cause of the observed differences. This is more plausible cause in the absence of dwarfing gene that affects internode length.

4.1.3.2 *Rate of increase in plant height*

Rate of increase in plant height was affected by water stress. The results of the analysis of variance indicated that the rates of height increase in the different FCs and in the 10 genotypes were highly significant whereas the genotype x FC interactions were not significant (Table 11). The fastest rates in height increase were observed at 100% FC and slowest at 50% FC (Table 12). The rate of increase in plant height at 50% FC was 0.14-0.15 cm day^{-1} slower than 75 and 100% FC. Compared to 100% FC, there was 33.30% reduction in the rate of height increase at 50% FC. Among genotypes, fastest rate of increase in plant height was measured in genotype 11 (0.6216) and the slowest rate of increase was in genotype 12 (0.2942) (Table 13, Figure 3) with a mean of 0.40. The rate of increase in plant height of all genotypes except genotype 11 was comparable to Banks. The ten genotypes had slower increase in plant height in drought conditions than at 100% FC, although it was statistically the same. The highest height reduction (50%) at 43 DAS was obtained in genotype 4 grown at 50% FC and the least was from genotype 6 with 14% at the same FC. The rate of increase in height of genotype 11 was least affected at 75% FC where as at 50% FC, Banks had fastest rate of increase in plant

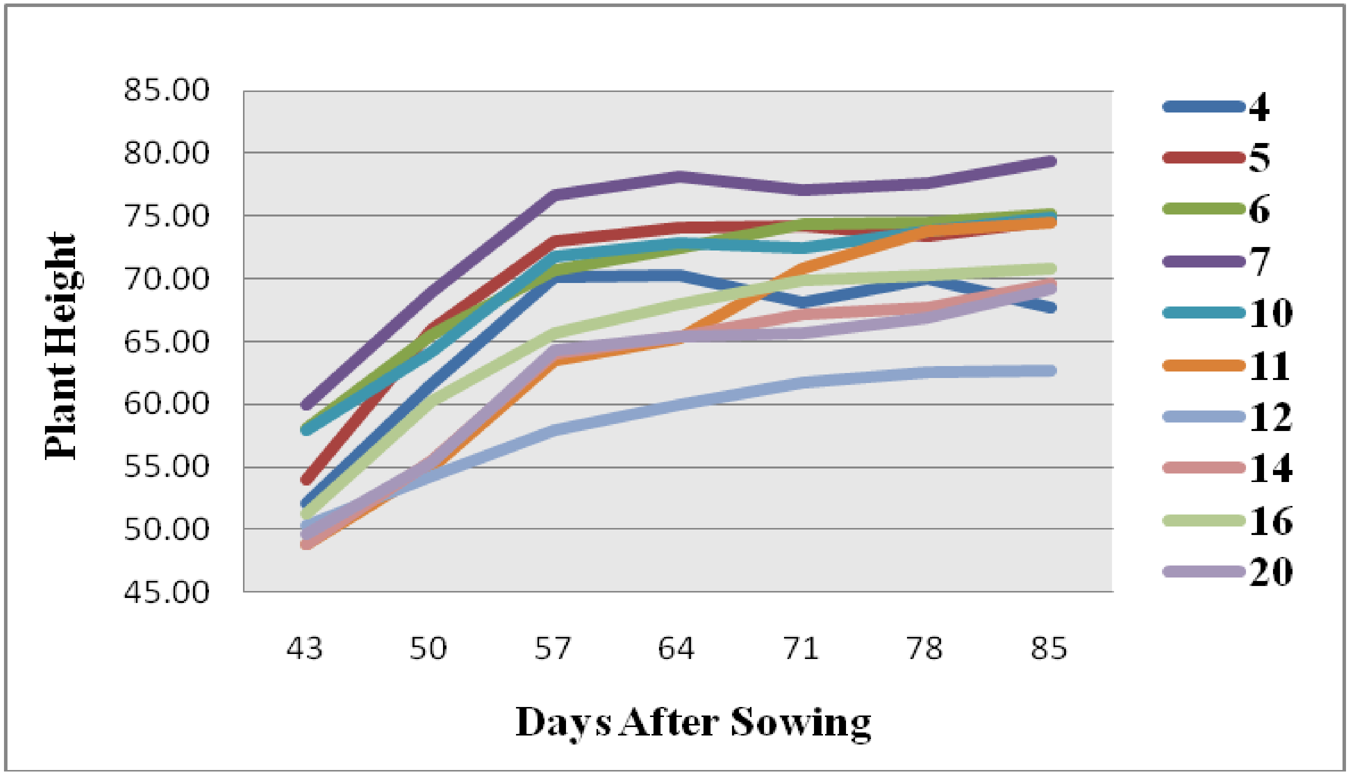

Figure 3. The rate of increase in plant height of ten genotypes across three field capacities.

height. The differences in rate of increase in plant height can be due to differences in cell elongation, internode elongation and number of nodes, the traits shown to be affected by drought and genotype (Guevarra and Chang, 1965).

4.1.4 Shoot and root biomass

4.1.4.1 *Shoot fresh and dry weights*

Significant differences were observed at the three FCs and among genotypes but not for the interaction of genotype and FC (Table 15) for both shoot fresh and dry weight. The shoot FW of plants at 50% FC was lowest (15.01 g) and was highest at 100% FC (41.26 g). The reduction in shoot FW due to water stress at 50% FC was 26.25 g and in 75% FC, it was 14.00 g (Table 16). At 50% FC the shoot DW was 3.99 g followed by 75% (7.94 g) and then by 100% FC (10.9 g). The decrease in shoot FW and DW due to stress was 13.89-26.28 g and 2.96-6.91 g, respectively. Reduced availability of water decreased shoot FW and DW by as much as 33.66-63.62% and 27.16-36.36%, respectively. Among genotypes, genotype 12 had the highest shoot FW (37.80 g) and DW (10.64 g) while the lowest shoot FW was from genotype 14 (21.72 g) and the lowest shoot DW was obtained from Banks (6.22 g) (Table 17). The mean of all the genotypes for shoot FW and DW was 28.07 g and 7.63 g, respectively. Seven genotypes had shoot FW comparable to Banks and only two stood apart (genotypes 11 and 12). Among high biomass genotypes, three genotypes were comparable in shoot FW to the heaviest genotype, genotype 12. Genotype 10 had shoot DW comparable to genotype 12. The shoot DWs of the remaining genotypes except genotype 6 were comparable to Banks.

Table 15. Mean squares of the ANOVA showing the effects of percentage field capacity, genotypes and their interaction on shoot fresh weight, shoot dry weight, root fresh weight, root dry weight and fresh and dry root:shoot ratio at Beaumont, Texas in summer 2009.

Source	df	Shoot weight (g)				Root weight (g)				Root:shoot ratio			
		Fresh		Dry		Fresh		Dry		Fresh		Dry	
		MS	Prob > F	MS	Prob > F	MS	Prob > F	MS	Prob > F	MS	Prob > F	MS	Prob > F
Genotype (G)	9	305.11	**	21.66	**	15.77	**	0.55	**	0.008	NS	0.003	**
FC†	2	5021.73	**	348.79	**	266.55	**	8.58	**	0.024	**	0.014	**
G x FC	18	56.75	NS‡	3.82	NS	3.06	NS	0.13	NS	0.003	NS	0.002	**

**Significance at $p \leq 0.01$.
†FC, field capacity.
‡NS, non-significant.

Table 16. Means of shoot fresh and dry weight, root fresh and dry weight and fresh and dry root:shoot ratio in three percentages of field capacity across ten genotypes at Beaumont, Texas in summer 2009.

% Field capacity	Shoot weight (g)		Root weight (g)		Root:shoot ratio	
	Fresh	Dry	Fresh	Dry	Fresh	Dry
50	15.01c	3.99c	2.08c	0.44c	0.14b	0.11c
75	27.37b	7.94b	5.05b	1.25b	0.18a	0.16a
100	41.26a	10.90a	8.15a	1.48a	0.20a	0.14b

Means with the same letters are not significantly different at 5% level of significance.

Table 17. Means of shoot fresh and dry weight, root fresh and dry weight and fresh and dry root:shoot ratio across drought levels of nine high biomass rice and cultivar Banks at Beaumont, Texas in summer 2009.

Genotype	Shoot weight (g)		Root weight (g)		Root:shoot ratio	
	Fresh	Dry	Fresh	Dry	Fresh	Dry
4	24.77c	6.27d	5.67abc	1.02abcd	0.221a	0.157ab
5	24.06c	7.28bcd	4.45bc	0.95bcd	0.179ab	0.138abc
6	31.71ab	8.58bc	5.26abc	1.19abc	0.168ab	0.143abc
7	24.23c	6.94cd	5.11bc	0.94bcd	0.197ab	0.132abcd
10	33.66ab	9.25ab	5.63abc	1.31a	0.160ab	0.135abcd
11	33.99a	8.32bcd	7.74a	1.46a	0.218a	0.169a
12	37.80a	10.64a	5.91ab	1.30ab	0.142b	0.109cd
14	21.72c	6.34d	3.14c	0.80cd	0.129b	0.127bcd
16	21.99c	6.54d	3.18c	0.66d	0.143b	0.102d
Banks	26.83bc	6.22d	5.61abc	1.02abcd	0.179ab	0.152ab
Means	28.07	7.64	5.17	1.065	0.174	0.136
CV%	23.95	24.68	45.65	39.29	37.95	25.64

Means with the same letters are not significantly different at 5% level of significance.

The highest shoot FW and DW of genotype 12 was 1.40 times and 1.71 times more than the FW and DW of Banks, respectively.

Although it was one of the shortest genotypes, genotype 12 was the earliest in tiller emergence and produced the most tillers, thereby increasing the shoot biomass. Moreover, this genotype was noted to have bigger tillers and wider and longer leaves relative to Banks. The shoot FW and DW was always lowest at 50% FC and best at 100% FC and this was true for all ten genotypes (Table 18). The shoot development of the ten genotypes was affected by drought. Numerically, least reduction was observed in genotype 11 and 12 and more in genotype 14 and 16 for these traits in three FCs. Earlier studies have similarly shown that water stress can reduce shoot growth (Hsiao and Acevedo, 1974; Price et al., 2002b; Boonjung and Fukai, 1996; Suralta and Yamauchi, 2008). The decreased shoot dry matter in drought stress might be due to the reduction of leaf area and slow photosynthesis rate (Sinaki et al., 2007; Zubarer et al., 2007). Reports indicated that there was a reduction in shoot dry matter due to drought stress in some of the genotypes (Lafitte et al., 2006). Removal of water in flooded field that is an induce drought was found to reduce plant height and greatest reduction was observed if the water was withheld for 28 days or more (Betlang, 2006).

4.1.4.2 ***Root fresh and dry weights***

The root FWs and DWs varied in three FCs and genotypes, and these differences were highly significant whereas the interaction of genotype and FC was not significant (Table 15). The root FWs were 2.08, 5.04 and 8.15 g at 50%, 75% and 100% FC, respectively. The root DWs of 100% and 75% FC were different (Table 16) and these two were significantly different to the lowest weight at 50% FC. The root DW at 100% FC was 3.36 times heavier than that at 50% FC and 1.18 times more than that at 75% FC. Among genotypes, the root FW ranged from 3.14-7.74 g with a mean of 5.17 g and the root DW ranged from 0.66-1.46 g with a mean 1.07 g. The highest root FW and root DW were obtained from genotype 11 with weights of 7.74 g and 1.46 g., respectively (Table 17). The lowest root FW was from genotype 14 and lowest root DW was from genotype 16. Comparison among means showed that the root FW and DW of the two extreme genotypes were significantly different from each other ($p \leq 0.01$). Root FW and DW of all high biomass genotypes were comparable to Banks. Among the selected high biomass rice, four genotypes had significantly lower root FW and DW than the heaviest entry (genotype 11). Compared to Banks, genotype 11 had 1.37 times and 1.43 times more root FW and DW, respectively. The root weight (FW and DW) was always lowest at 50% FC and best at 100% FC and this was true for all ten genotypes.

The root development of the ten genotypes was affected by drought. Least root FW and DW reduction were observed in genotype 11 and 12 and more in genotype 14 and 16 in three FCs. Similar results were obtained in chamber experiments conducted by Yamauchi et al. (1996) and in seedling evaluation made by Boonjung and Fukai (1996). At seedling stage, there was a 74% reduction of root growth under drought and water stress severely affects root biomass. Suralta and Yamauchi (2008) reported that nodal root production was reduced due to drought stress and this influenced the formation of root biomass. In water stressed soils, there was reduced oxygen supply, physical barrier like hardpans and poor adaptation of roots to aerobic condition that could limit

Table 18. Variations in shoot fresh and dry weight, root fresh and dry weight and fresh and dry root:shoot ratio among selected high biomass rice at three levels of field capacity at Beaumont, Texas in summer 2009.

Genotype	Shoot weight (g)						Root weight (g)						Root:shoot ratio					
	Fresh			Dry			Fresh			Dry			Fresh			Dry		
	100	75	50	100	75	50	100	75	50	100	75	50	100	75	50	100	75	50
4	31.68	26.61	11.64	8.24	6.57	2.85	8.33	5.23	2.33	1.42	1.02	0.40	0.26	0.20	0.20	0.17bcd	0.16bcde	0.14bcdefg
5	33.67	27.67	12.04	10.29	8.47	3.47	6.64	4.76	2.07	1.22	1.12	0.57	0.20	0.17	0.17	0.12defg	0.13bcdefg	0.16bcde
6	43.55	35.28	16.28	11.41	10.22	4.12	8.50	4.43	2.87	1.59	1.32	0.65	0.20	0.12	0.18	0.14bcdef	0.13cdefg	0.16bcde
7	33.89	27.74	11.05	9.29	8.57	2.96	6.95	6.60	1.78	1.20	1.26	0.34	0.20	0.23	0.17	0.13cdefg	0.14bcdef	0.13cdefg
10	50.53	32.60	17.85	13.79	9.33	4.64	9.34	5.26	2.28	1.70	1.81	0.42	0.18	0.16	0.13	0.12defg	0.19ab	0.09fgh
11	47.08	29.75	25.17	11.11	7.83	6.03	11.76	7.14	4.31	2.10	1.44	0.83	0.25	0.24	0.17	0.19ab	0.18abc	0.14bcdef
12	52.15	39.64	21.61	14.09	11.79	6.03	8.78	7.37	1.58	1.94	1.65	0.32	0.17	0.19	0.07	0.14bcdef	0.14bcdef	0.05h
14	38.81	17.09	9.27	10.58	5.44	2.99	5.93	2.59	0.91	1.22	0.87	0.33	0.15	0.14	0.10	0.12defg	0.16bcde	0.11efg
16	41.88	13.13	10.98	11.35	5.07	3.19	6.18	1.88	1.48	1.11	0.64	0.25	0.15	0.13	0.15	0.10fgh	0.13cdefg	0.08gh
Banks	39.39	22.72	12.11	8.91	5.46	2.96	9.09	5.14	0.87	1.32	1.39	0.21	0.23	0.21	0.07	0.15bcdef	0.24a	0.07gh

Means with the same letters are not significantly different at 5% level of significance.

exploitation of deeper soil layers hence reducing root biomass (Samson and Wade, 1998).

Differences in root growth for certain genotypes were also reported in rice by Kato et al. (2007). The high FW and DW of the best genotypes could be related to the length of root, number of roots particularly the lateral roots that were known to be important traits during drought stress (Lilley and Fukai, 1994b; Wang et al., 2009). The rooting habit of rice varieties differed laterally and vertically and these could be the causes of the variations in roots among the genotypes. The root distribution affects the capacity of the plant to extract water and nutrients particularly nitrogen. Deeply rooted and shallow rooted rice performed differently as these differed in ability to utilize the soil and applied nitrogen and water (Yoshida and Hasegawa, 1982). Cultivars tolerant to drought were deep rooting compared to shallow rooting susceptible ones (Minabe, 1951; Nemoto et al., 1998). Ingram et al. (1994) suggested that one of the important physiological traits for adaptation was how quickly the root traits respond to various soil-water levels.

4.1.4.3 *Root:shoot ratio*

The R:S ratio is important in characterizing deep rooting habit of rice critical in stress environment. The fresh and dry R:S ratio were affected by different FCs and were significantly different among genotypes. Interaction between genotype and FC for dry R:S ratio was significant but not for fresh R:S ratio (Table 15). The fresh R:S ratio at 100% FC (0.20) was the highest. It was comparable to R:S ratio at 75% FC but not at 50% FC. Similarly, the dry R:S ratios in all the three drought levels were significantly different ($p \leq 0.01$). Highest dry R:S ratio was obtained at 75% FC (0.16) followed by 100% (0.14) and lowest at 50% FC (0.11) (Table 16). The fresh R:S ratio of the genotypes across the drought levels ranged from 0.22-0.13 with a mean 0.17 and the dry R:S ratio of the genotypes ranged from 0.17-0.10 with a mean of 0.14 (Table 17). Although the fresh and dry R:S ratio of genotype 11 was the highest, it was comparable to five high biomass genotypes and Banks. The fresh and dry R:S ratios of all high biomass genotypes were comparable to Banks. The lowest fresh R:S ratio was from genotype 14 and the lowest dry R:S ratio was obtained from genotype 16 (Table 17). Except for genotypes 4 and 11, all the other genotypes were comparable to genotype 14 (lowest) for the fresh R:S ratio and four genotypes were comparable to lowest dry R:S ratio (genotype 16). The high R:S ratio of genotype 11, both in FW and DW, can been associated to its tillering ability and the emergence of tiller. For the interaction, the dry R:S ratio ranges from 0.05 at 50% FC to 0.24 at 75% FC with the mean of 0.14. The dry R:S ratio was highest in Banks at 75% FC and this was comparable to genotype 11 grown at 100% and 75% FC and genotype 10 at 75% FC. All the genotypes at any FC had dry R:S ratio comparable to Banks at 100% FC except genotype 12 and 15 at 50% FC. At 75% FC all the genotypes were comparable to genotype 11. The lowest dry R:S ratio was from genotype 12 at 50% FC and this was comparable to genotype 10, 16 and Banks at same 50% FC. Comparing dry R:S ratios at 100%, 75% and 50% FC for each genotype, genotype 11 and six other genotypes had similar dry R:S ratio, indicating that the balance of root and shoot growth was not affected by drought. However, these genotypes had variable dry R:S in each of the three FCs. Dry R:S ratio of Banks was severely affected by drought. It was the only genotype that the ratio was significantly different in three levels of FC. In stress condition, genotype 10, 12, 16 and Banks had the least ratios, indicating that these genotypes had poor system relative to the rest of the genotypes.

These results conformed to previous results reported by Asch et al. (2005). It was shown that R:S ratio decreased in conditions of progressive drought stress compared to fully watered plots. Hsiao (1982) reported that root growth was often favored over shoot growth when water becomes limiting. Larger R:S ratio is important in drought stress as it determines the ability of the genotype to absorb water from deeper soil layer and hence increase drought tolerance (Yoshida and Hasegawa, 1982). The interaction between genotype and stress levels for dry R:S ratio was also reported by Price et al. (2002b). It was found that the differences in R:S ratio was less in a stress at 49th day compared to stress at sowing and that in both treatments, one variety had smaller R:S ratio than the other variety. In barley, Jamieson et al. (1995) suggested that smaller root system made less water available to plant thereby reducing the R:S ratio.

Tillering habit was reported to be closely associated with rooting habit, and plant with early tillers tends to have a deep root system (Yoshida and Hasegawa, 1982). The early tillering genotypes in this study had also higher R:S ratios, thus may have better root system important in drought condition.

4.1.5 Plant biomass and dry matter production

4.1.5.1 *Total plant biomass*

The total fresh and dry biomass in all levels of FC and in all genotypes were significantly different but not for the interaction of genotype and % FC (Table 19). At 100% FC the total fresh and dry biomass was highest, having weights of 41.91 g and

Table 19. Mean squares of the ANOVA showing the effects of percentage field capacity, genotypes and their interaction on total fresh biomass, total dry biomass and percent dry matter at Beaumont, Texas in summer 2009.

Source	df	Total biomass				% Dry matter	
		Fresh		Dry			
		MS	Prob > F	MS	Prob > F	MS	Prob > F
Genotype (G)	9	425.55	**	27.59	**	62.59	**
FC[†]	2	7601.52	**	463.75	**	116.69	**
G x FC	18	72.02	NS[‡]	4.39	NS	17.47	NS

**Significance at $p \leq 0.01$.
[†]FC, field capacity.
[‡]NS, non-significant.

12.39 g, respectively (Table 20). Relative to 100% FC, there was 17.00 g and 3.20 g reduction in total fresh and dry biomass, respectively at 75% FC. Similarly, 17.08 g and 4.44 g reduction in fresh and dry biomass were obtained at 50% FC. Among genotypes, the total fresh biomass ranged from 24.18-43.71 g and the total dry biomass ranged from 7.14-11.94 g. The mean of all the high biomass genotypes across the three levels of FCs for the total FW and DW was 33.1 g and 8.70 g, respectively. The highest total FW and DW was obtained in genotypes 12 and 11, respectively and lowest total FW and DW was from genotypes 16 and 14, respectively. The mean total fresh biomass of genotypes 6, 10 and 11 were comparable to genotype 12 (Table 21). The total FW and DW of Banks were comparable to the total FW and DW of genotypes 4, 5, 7, 14 and 16. The lowest weight of total fresh biomass (from genotypes 14 and 16) was at least 4 g lower than the weights of the remaining genotypes. The high total biomass of genotype 11 and 12 can be attributed to either higher plant height, higher number of tillers, higher shoot and root weight as noted above. These traits were reported to increase total biomass (Vergara and Visperas, 1977). Similar to most of the traits presented above, the response of the ten genotypes was similar in each of the three FC levels for total fresh and dry biomass. The total fresh and dry biomass was highest at 100% FC and lowest at 50% FC and this was true for all the genotypes (Table 22). Numerically, least reduction was observed in genotype 4 and 5 for total fresh biomass whereas genotype 4 and 11 had least reduction for total dry biomass.

Table 20. Means of fresh and dry total biomass and percent dry matter in three percentages of field capacity across ten genotypes at Beaumont, Texas in summer 2009.

% Field Capacity	Total biomass		% Dry matter
	Fresh	Dry	
50	17.08c	4.44c	26.52b
75	32.41b	9.19b	29.27a
100	49.41a	12.39a	25.14b

Means with the same letters are not significantly different at 5% level of significance.

Table 21. Means of fresh and dry total biomass and percent dry matter across drought levels of nine high biomass rice and cultivar Banks at Beaumont, Texas in summer 2009.

Genotype	Total biomass		%
	Fresh	Dry	Dry matter
4	30.44bcd	7.28d	24.17cd
5	28.51cd	8.23bcd	28.89ab
6	36.97abc	9.78abc	26.27bcd
7	29.33cd	7.88cd	26.83bcd
10	39.29ab	10.56ab	26.56bcd
11	41.73a	9.78abc	23.52d
12	43.71a	11.94a	27.43abc
14	24.86d	7.14d	30.60a
16	24.18d	7.20d	31.09a
Banks	32.44bcd	7.24d	23.12d
Means	33.146	8.703	26.848
CV%	25.33	25.41	12.99

Means with the same letters are not significantly different at 5% level of significance.

Table 22. Variations in total fresh and dry biomass and percent dry matter among selected high biomass rice at three levels of field capacity at Beaumont, Texas in summer 2009.

Genotype	Total biomass						% Dry matter		
	Fresh			Dry					
	100	75	50	100	75	50	100	75	50
4	40.01	31.84	13.97	9.66	7.59	3.25	24.47	23.92	24.10
5	40.31	32.43	14.11	11.51	9.58	4.04	28.53	29.53	28.84
6	52.05	39.71	19.15	13.00	11.54	4.77	24.96	28.96	24.89
7	40.84	34.34	12.82	10.49	9.84	3.30	25.85	28.71	25.93
10	59.87	37.86	20.13	15.48	11.14	5.06	25.83	29.24	24.62
11	58.84	36.89	29.47	13.21	9.27	6.86	22.02	25.20	23.33
12	60.93	47.01	23.18	16.04	13.44	6.35	26.26	28.63	27.38
14	44.74	19.68	10.18	11.80	6.31	3.32	26.54	32.45	32.81
16	48.06	15.02	12.46	12.45	5.70	3.44	25.74	40.05	27.49
Banks	48.48	27.86	12.97	10.23	6.85	3.16	21.26	24.51	24.52

Reduction in fresh and dry weight of biomass due to drought has been reported for conventional rice grown for grain but not for high biomass rice. Pantuwan et al.

(2002b) observed a 39% reduction in drought stressed crops compared to fully irrigated crops. Similar results were observed by Bernier et al. (2007) in a much recent study. The very high reduction in biomass yield (65%) at 50% FC suggests the general sensitivity of all the genotypes. These reductions might be due to low net photosynthesis, low nutrition associated oxidative damage to shoot tissues (Zhang and Kirkham, 1996), or low reduction of root thickness in drought environment (Azhiri-Sigari et al., 2000). In barley, the reduction of biomass was associated to decrease in radiation interception, and reduced rate and duration of growth (Jamieson et al., 1995).

4.1.5.2 *Percent dry matter*

The variation in % DM was significantly different among levels of FC, and genotypes but not their interaction (Table 19). Among FCs, the highest % DM was at 75% FC (29.27%) and the lowest was at 100% FC (25.14%). Mean comparison among FCs indicated that % DM at 100% and 50% FC were comparable and these were significantly different than % DM at 75% FC. Higher % DM at 75% FC could be due to stress signal that caused faster accumulation of photoassimilates (Matsuo et al., 2007) while the very low % DM in severe stress (50% FC) might be due to decline in photosynthesis obviously leading to a reduction in dry matter accumulation. The plant at 100% FC had highest FW and DW than plant at 50% FC but had comparable % DM suggesting that it was more succulent and had more water than those in drought conditions.

The amount of dry matter is important if these genotypes will be used as feedstocks for bioenergy. Across FCs, the % DM of genotype 16 was highest (31.09%)

and genotype 11 had the least (23.52%). The mean % DM of the selected high biomass rice genotypes was 26.84% (Table 21). Genotypes 5, 12, 14 and 16 had comparable % DM and these were significantly higher than Banks. All the remaining genotypes were comparable to Banks, the conventional rice cultivar. The % DM of genotype 16 was 1.34 times more than Banks. The interaction of genotype and % FC was not significant for % DM indicating that the response of the ten genotypes was similar in each of the three FC levels for % DM.

The amount of dry matter from a feedstock is critical in gas formation, total organic carbon content, and phenols concentration during gasification (Kruse et al., 2003). One of the best genotypes for total and dry biomass had the least % DM indicating that it had less dry matter $unit^{-1}$ of fresh biomass harvested, and may not be the best genotype as feedstock. Selection for both high total biomass and % DM has to be considered in developing high biomass rice or bioenergy crop.

The best performing genotypes were very impressive as these genotypes had the best traits measured in this study. Simple correlation was conducted to determine the relationship of these traits to total fresh and dry biomass yield (Table 23). Results indicated that total fresh and dry biomass were significantly and positively correlated with fresh shoot weight, dry shoot weight, fresh root weight and dry root weight, rate of increase in plant height, plant height at 43 and 85 DAS, rate of tiller production and number of tillers at 43 and 85 DAS. Total fresh and dry biomass was significantly and negatively correlated with the days for first tiller emergence whereas both were not significantly correlated with leaf counts at 43 and 85 DAS and with the rate of increase in leaf count. These traits that were correlated with total fresh and dry biomass maybe useful intermediate traits for selection in increasing biomass yields.

The yield stability under drought stress depends on accumulation of dry matter and its effective partitioning to plant parts of economic importance (Kumar et al., 2006). It has been reported by Pantuwan et al., (2002) that a few physio-morphological characters confer drought resistance in rice leading to better performance of those genotypes under drought conditions. In the present study, genotype 12 had the best overall performance in drought condition as it had first tillers emerged, maximum number of tillers, shortest plant height, highest shoot fresh and dry weight, total fresh and dry biomass.

Table 23. Correlation between various traits and total fresh and dry biomass of high biomass rice genotypes grown at various levels of field capacity at Beaumont, Texas in summer 2009.

Trait	Total biomass	
	Fresh	Dry
Days to first tiller emergence	-0.73**	-0.73**
Number of tillers at 43 DAS[¶]	0.71**	0.70**
Number of tillers at 85 DAS	0.45**	0.45**
Rate of tiller production	0.04	0.03
Number of leaves at 43 DAS	-0.15	-0.17
Number of leaves at 85 DAS	-0.05	-0.05
Rate of increase in number of leaves	-0.06	-0.07
Plant height at 43 DAS	0.69**	0.72**
Plant height at 85 DAS	0.68**	0.69**
Rate of increase in plant height	0.26*	0.22*
Shoot fresh weight	0.99**	0.97**
Shoot dry weight	0.96**	0.99**
Root fresh weight	0.89**	0.82**
Root dry weight	0.87**	0.88**
Fresh root:shoot ratio	0.38**	0.30**
Dry root:shoot ratio	0.23*	0.19

*Significance at $p \leq 0.05$.
**Significance at $p \leq 0.01$.
[¶]DAS, days after sowing.

4.2 Experiment 2: Response of Selected High Biomass Rice to Rainfed and Flooded Conditions

Rice production consumes more water than production of any other crop, which is up to six times more than that required by wheat (FAO, 2004). Increasing rice production to feed the increasing world population that is rice dependent will divert more water for rice production. Fresh water is a resource that is constantly getting scarce and currently 31 countries are facing water shortages (CGIAR, 1999). The growing water shortage implies the need to devise methods of growing rice with less water. The future of rice grain production will depend heavily on developing and adopting strategies and practices that will use water efficiently in irrigation scheme (Guerra et al., 1998). For high biomass rice, environment other than the fully irrigated areas will be the best option to avoid reduction in grain rice if biomass rice will be grown as feedstock to biorefinery. One of the objectives in this thesis was to study the response of selected high biomass rice lines to rainfed (non-flooded) and flooded condition.

4.2.1 Plant height

The variations in plant height at harvest among genotypes were not significant but the differences in two environments and genotype x environment interaction were highly significant (Table 24). The mean height of the 20 genotypes grown in flooded condition was higher (115.75 cm) than those in rainfed (103.80 cm). The mean height of genotypes at harvest across two environments ranged between 100.83-115.29 cm with a mean of 109.79 cm (Table 25). The tallest was genotype 10 and the shortest was genotype 4 but all genotypes were comparable to Banks. Considering the interaction of genotype and the environment, the tallest was genotype 2 in flooded (135.00 cm) and the shortest was the same genotype grown in rainfed condition (93.67 cm). The height of genotype 2 in flooded was comparable to all genotype x environment combinations except genotypes 2, 4, 5, 12, 14, 17, 18 and 19 grown in rainfed. The shortest height, however, was comparable to all genotype x environment combinations except genotype 2 and 18 grown in flooded field. All of the selected high biomass rice genotypes had mean height comparable to Banks in both environments. All genotypes had similar heights when grown in rainfed and flooded condition except genotype 2 that had 30%

reduction in height when grown in rainfed field. Generally, shorter plants were found in rainfed plots except for genotypes 10, 11 13 and Bank that were taller in rainfed plots.

Table 24. Mean squares of the ANOVA showing the effects of environment, genotypes and their interaction on the average height at Beaumont, Texas in summer 2009.

Source	df	Average height (cm)	
		MS	Prob > F
Environment	1	2874.00	**
Genotype (G)	19	62.47	NS‡
Environment x G	19	205.19	**

**Significance at $p \leq 0.01$.
‡NS, non-significant.

These results conform to previous studies showing that plants grew taller in flooded condition than in non-flooded condition (Chaudhry and McLean, 1963; Price et al., 2002b; Kamoshita and Abe, 2007; Patel et al., 2010). Rainfed field is considered a stress environment where drought is common but salinity and nutrient problem may also occur. Reduction in plant height of varieties under rainfed condition may be due to water stress that limits cell elongation resulting in reduction of internodal length, and eventually, shorter plant height (Patel et al., 2010). Plant height is an important plant architectural trait in increasing biomass (Yuan et al., 2008; Salas-Fernandez et al., 2009). All of the genotypes were generally taller than typical U.S. rice variety since these high biomass rice lines were initially selected for tallness and late maturity. Most of the semi-dwarf U.S. varieties have *sd-1*, the green revolution gene but not Banks. The similarity in height to Banks, therefore, suggests that like Banks, these genotypes may not have the dwarfing gene, *sd-1*.

Table 25. Plant height of selected high biomass and Banks in two environments at Beaumont, Texas in summer 2009.

Genotype	Average height — Environment: Rainfed	Average height — Environment: Flooded	Mean
1	102.25abc	125.17abc	113.71
2	93.67c	135.00a	114.33
3	108.00abc	118.17abc	113.08
4	95.50bc	106.17abc	100.83
5	98.67bc	114.33abc	106.50
6	103.50abc	120.33abc	111.92
7	103.50abc	122.67abc	113.08
8	110.83abc	111.50abc	111.17
9	110.33abc	111.75abc	111.04
10	119.92abc	110.67abc	115.29
11	111.33abc	105.83abc	108.58
12	99.92bc	127.17abc	113.54
13	108.00abc	101.33abc	104.67
14	97.67bc	118.42abc	108.04
15	109.33abc	111.67abc	110.50
16	103.50abc	112.33abc	107.92
17	100.50bc	107.42abc	103.96
18	96.00bc	128.33ab	112.17
19	95.50bc	125.17abc	110.33
Banks	108.08abc	102.33abc	105.21
Means	103.79	115.78	109.79
CV%			7.35

Means with the same letters are not significantly different at 5% level of significance.

4.2.2 Tillering related traits

The number of tillers meter^{-1} row at 56 and 105 DAS and rate of increase in number of tillers meter^{-1} did not show significant variation between flooded and rainfed environment. However, variations among the genotype for these traits were highly significant. The interaction between genotype and environment was significant for tiller number at 105 DAS but not for tillering rate and tiller number at 56 DAS (Table 26). At 56 DAS, plants in flooded condition had four more tillers than rainfed in one meter row length and at 105 DAS, it was increased to ten tillers but these differences were not statistically different. Similarly, the rate of increase in tillers of 0.55 and 0.66 in flooded and rainfed condition, respectively were not significant. There were a lot of variations in the number of tillers meter^{-1} at 56 DAS and 105 DAS and the rate of tiller production among the 20 genotypes (Table 27). The number of tillers ranged from 103.32-196.80 at 56 DAS, and at 105 DAS, it ranged from 119.72-217.30. Genotype 11 had the highest number of tillers at both 56 DAS and 105 DAS. The lowest tiller count at 56 DAS was from genotype 17 and at 105 DAS, genotype18 had the lowest count. At 56 DAS and 105 DAS, all the genotypes were comparable to Banks except for genotype 11. Genotype 11 had 1.55 and 1.43 times more tillers than Banks at 56 and 105 DAS. For tiller production, the fastest was obtained in genotype 7 and slowest was from genotype 6. Although, genotype 6 had lowest rate of increase in number of tillers, it was comparable to all of the genotypes except genotypes 4, 7 and 9. The rate of increase in number of tillers of these extreme genotypes was significantly different from each other. All the genotypes had rates of increase in number of tillers comparable to Banks.

Table 26. Mean squares of the ANOVA showing the effects of environment, genotypes and their interaction on tillers meter^{-1} at 56 DAS and 105 DAS, rate of increase in tillers meter^{-1} and tillers plant^{-1} at Beaumont, Texas in summer 2009.

Source	df	Tillers meter^{-1}				Rate of increase in tillers meter^{-1}		Tillers plant^{-1} at 105 DAS	
		56 DAS[¶]		105 DAS					
		MS	Prob > F	MS	Prob > F	MS	Prob > F	MS	Prob > F
Environment	1	336.20	NS[‡]	1840.89	NS	0.24	NS	173.95	**
Genotype (G)	19	1874.90	**	3252.22	**	0.46	**	44.18	**
Environment x G	19	825.99	NS	1217.19	*	0.14	NS	16.09	*

*Significance at $p \leq 0.05$.
**Significance at $p \leq 0.01$.
¶DAS, days after sowing.
‡NS, non-significant.

Considering the interaction between environment and genotype (Table 28), tiller count at 56 DAS ranged from 86.92 (genotype 17 in flooded) to 218.12 (genotype 11 in flooded) and the rate of tiller production ranged from -0.12 (genotype 6 in flooded) to 1.75 (genotype 7 in rainfed). Although these values were statistically the same, numerical differences for each genotype were noted in two environments. Some had more tillers at 56 DAS in rainfed than flooded like genotypes 3, 4, 8, 12, 16, 17 and 19 and were faster in tiller production. At 105 DAS, the tiller count ranged from 103.32-236.16 tillers. The highest was from genotype 11 in flooded field and lowest was counted in genotype 17 grown in flooded condition. All the genotypes except genotypes 8, 17 and 18 in flooded condition and genotypes 2, 13 and 18 in rainfed condition had tiller count comparable to genotype 11 in flooded condition. Except for genotype 11 in flooded condition and genotypes 7, 9, 12 and 16 in rainfed condition, all the other genotypes x environment interaction were comparable to genotype 17 in flooded condition. Genotype 11 which had the highest number of tillers had 1.53 times more

Table 27. Mean of tillers meter^{-1}, rate of increase in tillers meter^{-1} and tillers plant^{-1} across two environments of nineteen high biomass rice and cultivar Banks at Beaumont, Texas in summer 2009.

Genotype	Tillers meter^{-1}		Rate of increases in tillers meter^{-1}	Tillers plant^{-1} at 105 DAS
	56 DAS¶	105 DAS		
1	126.28bc	158.26abc	0.70abc	15.04abcd
2	118.08c	136.12bc	0.40abc	10.63cd
3	113.16c	148.42bc	0.79abc	16.94abcd
4	136.12bc	190.24ab	1.14a	18.06abc
5	123.82bc	143.50bc	0.44abc	11.98bcd
6	139.40bc	144.32bc	0.10c	12.00bcd
7	147.60abc	201.72ab	1.15a	16.62abcd
8	126.28bc	144.32bc	0.43abc	11.85bcd
9	144.32abc	197.62ab	1.08ab	14.76abcd
10	134.48bc	181.22abc	0.92abc	14.01bcd
11	196.80a	217.30a	0.46abc	22.08a
12	176.30ab	198.44ab	0.43abc	16.67abcd
13	113.16c	137.76bc	0.53abc	11.80bcd
14	134.48bc	140.22bc	0.11bc	10.89cd
15	129.56bc	177.12abc	1.03abc	15.94abcd
16	140.22bc	181.22abc	0.89abc	16.85abcd
17	103.32c	122.18c	0.43abc	9.55d
18	113.16c	119.72c	0.15bc	11.31cd
19	136.94bc	153.34abc	0.36abc	19.04ab
Banks	126.28bc	151.70abc	0.57abc	17.08abcd
Means	133.98	162.23	0.6055	14.65
CV%	15.73	15.54	59.85	19.88

Means with the same letters are not significantly different at 5% level of significance.
¶DAS, days after sowing.

tiller than Banks in flooded conditions. Banks, however, had 1.49 times more number of tillers than lowest tillering genotype 17 in flooded condition. Similar to tiller count at 56

DAS, all genotypes had statistically same tiller count at 105 DAS when grown in either environments. However, some genotypes seem to favor one environment. For instance, seven genotypes tended to produce relatively more tillers in rainfed than in flooded.

The number of tillers plant^{-1} at 105 DAS in flooded was 16.13 and this was significantly higher than in rainfed with 13.18 tillers. Tillers count plant^{-1} in flooded was 1.22 times more than rainfed. Among genotypes, the number of tillers ranged from 9.55-22.08 tillers with a mean of 14.66 tillers (Table 28). Genotype 11 had highest number of tillers while genotype 17 had lowest tiller count. All genotypes had tiller count comparable to Banks. For genotype x environment interaction, the number of tillers plant^{-1} ranged from 6.60 (genotype 13 in flooded) to 24.00 (genotype 11 in flooded). Genotypes 6, 8, and 17 in flooded and genotypes 2, 3, 5, 13, 14, 17 and 18 in rainfed condition were significantly different from genotype 11 in flooded. Genotype 13 in flooded was comparable to all genotype x environment interactions except genotypes 3, 15 and 19 in flooded, and genotype 11 in both rainfed and flooded. All genotypes grown either in flooded or rainfed were comparable to Banks. The extreme genotypes were significantly different from each other and genotype 11 in flooded had 3.63 times more number of tillers plant^{-1} at 105 DAS than genotype 13 in rainfed.

The results suggest that the high biomass rice genotypes will have the same tillering ability in both environments. Similar results were obtained in recent experiments where there was no significant difference in maximum tiller number between flooded and non-flooded conditions (Cairns et al., 2009; Yan et al., 2010). The reduction in tiller number plant^{-1} can be attributed to drought stress in rainfed environment that also affected plant height as noted earlier. Owusu-Sekyere (2005) reported that as early as sixth week (42 DAS), the number of tillers in flooded plants was significantly greater than that for rainfed plants. The results highlighted the superior tillering ability of genotype 11. Among the 20 genotypes, this genotype produced the highest number of tillers meter^{-1} and tillers plant^{-1}. The same genotype was the best in the drought study, producing 3.31 more tillers than Banks and was the fastest in producing tillers.

4.2.3 Days to 50% heading

Similar to plant height and tiller number plant^{-1}, the number of days to 50% heading was different in the two environments. The variation among genotypes to 50% heading was highly significant while the environment x genotype interaction was significant (Table 29). The plants reached 50% heading significantly earlier in flooded than rainfed (93.92 DAS vs 111.15 DAS). Flowering in rainfed was delayed by more than two weeks (17.23 days). Among the genotypes, the number of days to 50% heading ranged from 93-113 with a mean of 102.54 days (Table 30). Genotype 10 was the fastest to attain 50% heading whereas genotype 12 was the last to reach 50% heading. Genotypes 8, 16, 17 and 18 were comparable to the fastest heading genotype while genotypes 3, 5, 11 and 19 were comparable to the slowest heading genotype. The two extreme genotypes were significantly different from each other. Genotype 10 reached 50% heading 9 days earlier than Banks and genotype 12 reached 50% heading 11 days later than Banks. For the interaction, the number of days to 50% heading ranged from 86.50 days (genotype 18 in flooded) to 123.50 days (genotype 12 in rainfed). The

Table 28. Tillers meter^{-1}, rate of increase in tillers meter^{-1} and tillers plant^{-1} of selected high biomass rice and Banks in two environments at Beaumont, Texas in summer 2009.

Genotype	Tillers meter^{-1}				Rate of increases in tillers m^{-1}		Tillers plant^{-1} at 105 DAS	
	56 DAS[¶]		105 DAS					
	Environment		Environment		Environment		Environment	
	Rainfed	Flooded	Rainfed	Flooded	Rainfed	Flooded	Rainfed	Flooded
1	118.08	134.48	144.32abcd	172.20abcd	0.58	0.82	14.67abcde	15.42abcde
2	108.24	127.92	126.28bcd	145.96abcd	0.41	0.39	8.48de	12.79abcde
3	116.44	109.88	149.24abcd	147.60abcd	0.79	0.79	11.38bcde	22.50ab
4	152.52	119.72	206.64abcd	173.84abcd	1.17	1.11	18.46abcde	17.67abcde
5	111.52	136.12	132.84abcd	154.16abcd	0.44	0.45	10.13cde	13.83abcde
6	139.40	139.40	155.80abcd	132.84abcd	0.33	-0.12	13.88abcde	10.13cde
7	149.24	145.96	229.60ab	173.84abcd	1.75	0.56	15.58abcde	17.67abcde
8	145.96	106.60	159.08abcd	129.56bcd	0.28	0.57	14.00abcde	9.70cde
9	165.64	123.00	219.76abc	175.48abcd	1.14	1.03	13.40abcde	16.13abcde
10	124.64	144.32	190.24abcd	172.20abcd	1.23	0.61	12.95abcde	15.08abcde
11	175.48	218.12	198.44abcd	236.16a	0.50	0.41	20.17abcd	24.00a
12	183.68	168.92	216.48abc	180.40abcd	0.60	0.26	15.00abcde	18.33abcde
13	88.56	137.76	108.24d	167.28abcd	0.46	0.60	6.60e	17.00abcde
14	150.88	118.08	147.60abcd	132.84abcd	-0.08	0.30	8.28de	13.50abcde
15	124.64	134.48	162.36abcd	191.88abcd	0.81	1.24	12.38abcde	19.50abcd
16	164.00	116.44	218.12abc	144.32abcd	1.13	0.65	15.13abcde	18.58abcde
17	119.72	86.92	141.04abcd	103.32d	0.48	0.38	8.60cde	10.50bcde
18	109.88	116.44	114.80cd	124.64bcd	0.12	0.17	8.75cde	13.88abcde
19	150.88	123.00	170.56abcd	136.12abcd	0.39	0.33	17.33abcde	20.75abc
Banks	121.36	131.20	149.24abcd	154.16abcd	0.68	0.46	18.50abcde	15.67abcde

Means with the same letters are not significantly different at 5% level of significance.
[¶]DAS, days after sowing.

earliest genotype 18 was not comparable to all genotypes in rainfed condition and genotypes 2, 5, 9, 11, 12 in flooded condition. The late heading genotype 12 was comparable to genotypes 3, 5, 9, 11 and 19 in rainfed condition. Banks in rainfed was similar in heading to all genotypes in the same environment except eight genotypes but Banks in flooded was heading similarly to all genotypes except three. Genotype 18 in flooded headed nine days earlier than Banks in flooded whereas genotype 12 in rainfed headed thirteen days later than Banks in rainfed.

Results indicated that heading varies among genotypes and environments. Heading is an important trait in both grain and biomass yield. Long growth duration variety is generally associated with higher dry matter yield than those with short growth duration, and varieties with long duration of vegetative growth and high weight per ratoon tillers produce high dry matter yield in the ratoon crop (Nakano and Morita, 2007). Bouman and Tuong (2001) reported the same delay in flowering in rainfed plots. It was observed that most of the genotypes had growth duration longer by 4-17 days in rainfed condition. At least seven days delay in flowering was reported in studies conducted in non-saturated soil and not flooded aerobic rice cultivation (Yan et al., 2010). Drought stress in rainfed environment is severe than in non-saturated soil, thus further delay as observed in our plot is possible. Lilley and Fukai (1994b) showed that a large delay in flowering and the magnitude of this delay was associated with severity of drought conditions.

Table 29. Mean squares of the ANOVA showing the effects of environment, genotypes and their interaction on days to 50% heading at Beaumont, Texas in summer 2009.

Source	df	Days to 50% heading	
		MS	Prob > F
Environment	1	5934.01	**
Genotype (G)	19	143.11	**
Environment x G	19	22.85	**

**Significance at $p \leq 0.01$.

Table 30. Days to 50% heading of selected high biomass rice and Banks at two environments at Beaumont, Texas in summer 2009.

Genotype	Days to 50% heading		Mean
	Environment		
	Rainfed	Flooded	
1	109.50defgh	92.50lmno	101.00efgh
2	111.00def	96.50jklmn	103.75cdef
3	121.50ab	95.50jklmno	108.50abc
4	110.00defg	93.00lmno	101.50defg
5	122.50ab	101.00ghijkl	111.75ab
6	109.50defgh	96.50jklmn	103.00cdef
7	112.00cde	90.00mno	101.00efgh
8	102.50fghijk	88.00no	95.25hij
9	114.50abcd	97.50ijklm	106.00bcde
10	97.00ijklmn	89.00mno	93.00j
11	122.00ab	101.00ghijkl	111.50ab
12	123.50a	102.50fghijk	113.00a
13	114.00bcd	93.50klmno	103.75cdef
14	106.00defghi	93.00lmno	99.50fghi
15	111.00def	96.50jklmn	103.75cdef
16	104.00efghij	89.50mno	96.75ghij
17	100.50hijkl	89.00mno	94.75ij
18	101.00ghijkl	86.50o	93.75ij
19	120.50abc	94.00klmno	107.25abcd
Banks	110.50def	93.50klmno	102.00defg
Means	111.15	93.925	102.5375
CV%			2.121

Means with the same letters are not significantly different at 5% level of significance.

4.2.4 Biomass yield (kg ha^{-1})

The biomass yield at full crop maturity of genotypes in flooded condition was 29,865.87 kg ha^{-1} and this was significantly higher than biomass yield in rainfed of 24,935.84 kg ha^{-1} (Table 31). The biomass of the 20 selected high biomass rice genotypes across two environments ranged from 14689.08 to 45129.56 kg ha^{-1} (Table 32). The variation among genotypes in biomass yield (kg ha^{-1}) was highly significant. Genotype 11 had the highest biomass whereas the early flowering entry, genotype 18, had the lowest. Although genotype 11 had highest biomass yield, it was comparable to genotypes 1, 3, 4, 6, 12, 13, 16, 19 and Banks. All of the genotypes except genotypes 3, 6 and 11 were comparable to genotype 18 having the lowest weight of biomass. The biomass yield of genotype 11 was 1.62 times that of Banks. The interaction of genotype and environment was not significant for biomass yield. The lowest biomass was obtained in genotype 10 in rainfed (13,297 kg ha^{-1}) and the highest was from genotype 11 in both flooded and rainfed with nearly identical yield of 45,193 and 45,065 kg ha^{-1}, respectively. In most cases the genotype had higher biomass yield in flooded field but genotypes 2, 7, 14, 16, 18 and 19 had numerically more biomass yield in rainfed environment. Genotype 11 had the highest biomass yield and it performed equally in flooded and rainfed environments while genotype 12 (39,513 kg ha^{-1}) was closely following genotype 11 when grown in flooded field. These two genotypes were also the best in the drought experiments.

The biomass generated in flooded condition was 1.19 times more than in rainfed condition suggesting that in general, these genotypes preferred flooded condition. The plants in flooded field were mostly taller, produced more tillers, and flowered earlier. These traits may have favored generation of more biomass. Lower biomass yield have been reported in the development of aerobic rice, upland rice and rainfed rice when

Table 31. Mean squares of the ANOVA showing the effects of environment, genotypes and their interaction on the biomass yield at Beaumont, Texas in summer 2009.

Source	df	Biomass yield (kg ha^{-1})	
		MSE	Prob > F
Environment	1	485985208.00	**
Genotype (G)	19	194328340.00	**
Environment x G	19	71746067.00	NS‡

**Significance at $p \leq 0.01$.
‡NS, non-significant.

grown in flooded field. Evaluating four rice cultivars (two aerobic and two conventional rice cultivars) in flooded and non-flooded, Yan et al. (2010) reported that biomass was significantly affected by water regime. Similarly, total dry matter in flooded condition was more than aerobic condition (Cairns et al., 2009; Patel et al., 2010). The high biomass rice genotypes followed the same trend indicating that these genotypes are not different to the aerobic rice and upland rice and it will behave different if grown in non-flooded soil.

The high biomass of genotype 11 can be attributed to high number of tillers meter^{-1} at both 56 and 105 DAS and high number of tillers plant^{-1} at 105 DAS. Simple correlations indicated that biomass yield was significantly and positively correlated with tillers meter^{-1} at 56 DAS, 105 DAS and number of tillers plant^{-1} at 105 DAS (Table 33).

The tillers at 56 DAS were found significantly and positively correlated with tillers

Table 32. Biomass yield of selected high biomass rice and Banks in two environments at Beaumont, Texas in summer 2009.

Genotype	Biomass yield (kg ha^{-1}) Environment		Mean
	Rainfed	Flooded	
1	25178.72	30148.16	27663.44abc
2	26147.52	23175.60	24661.56bc
3	26209.68	43963.92	35086.80ab
4	27890.24	36733.76	32312.00abc
5	17171.84	24788.96	20980.40bc
6	31699.92	42868.56	37284.24ab
7	28985.04	22402.24	25693.64bc
8	20786.08	31052.56	25919.32bc
9	23046.80	26469.52	24758.16bc
10	13297.76	20530.72	16914.24c
11	45065.44	45193.68	45129.56a
12	18592.56	39513.04	29052.80abc
13	26663.28	37767.52	32215.40abc
14	27436.08	23046.80	25241.44bc
15	19107.76	25114.32	22111.04bc
16	35378.00	23758.56	29568.28abc
17	14460.32	29503.60	21981.96bc
18	15497.44	13880.72	14689.08c
19	31117.52	26988.08	29052.80abc
Banks	24984.96	30405.20	27695.08abc
Means	24935.85	29865.28	27400.56
CV%			24.53

meter^{-1} at 105 DAS, number of tillers plant^{-1} at 105 DAS and days to 50% heading. Average height was significantly and negatively correlated with days to 50% heading.

The selection of improved cultivars in rainfed areas is challenging as the success depends on the environments, trait identification which causes improved resistance and developing effective selection methods for useful traits and understanding the performance of these modern cultivars in different environments (Kumar et al., 2006). In the present study genotype 11 performed the best as it had maximum number of tillers/750 cm^2, maximum tillers/plant, delayed heading and highest dry weight of above ground biomass. Delayed heading has been shown to be used as an integrative trait to identify drought-tolerant cultivars (Pantuwan et al., 2001).

Table 33. Correlation among various traits of high biomass rice genotypes grown in two different environments at Beaumont, Texas in summer 2009.

Trait	Average height	Tillers meter^{-1} at 56 DAS¶	Tillers meter^{-1} at 105 DAS	Rate of tiller production	Tillers plant^{-1} at 105 DAS	Days to 50% heading
Average Height	1					
Tillers meter^{-1} at 56 DAS	-0.01	1				
Tillers meter^{-1} at 105 DAS	-0.06	0.80**	1			
Rate of tiller production	-0.09	0.02	0.60**	1		
Tillers plant^{-1} at 105 DAS	0.14	0.46**	0.57**	0.34**	1	
Days to 50% heading	-0.43**	0.24*	0.24*	0.09	-0.11	1
Biomass yield (kg ha^{-1})	0.04	0.32**	0.27*	0.04	0.45**	0.01

*Significance at $p \leq 0.05$.
**Significance at $p \leq 0.01$.
¶DAS, days after sowing.

CHAPTER V

SUMMARY AND CONCLUSIONS

Rice germplasm characterization and evaluation are important in breeding new varieties and developing varieties for specific stress conditions. Research experiments were conducted during the summer season of 2009 at the Texas AgriLife Research and Extension Center, Beaumont, Texas to study the responses of high biomass rice breeding genotypes to drought, rainfed and flooded conditions. Along with one conventional rice variety, Banks, nine genotypes were studied in the greenhouse and 19 genotypes in the field. Ten genotypes were common in two experiments. These genotypes were the best in 2008 field trial of selected high biomass rice genotypes.

In the greenhouse experiment, the genotypes were exposed to drought treatment given in three different levels of 100%, 75% and 50% FC. The treatment combinations were arranged in a completely randomized design with three replications. Whereas in the field, the experiment was arran6ged as a split-plot design with the environment namely: rainfed and flooded as the main plot treatment and the twenty genotypes as the sub-plot treatments with two replications.

The availability of water affected the agronomic traits and biomass production. Most of the genotypes performed better under non-stressed conditions. In the greenhouse, there was a decrease in tillering related traits and plant height under water stress conditions. Emergence of the first tiller was delayed by 4.65-8.92 days in 75% and 50% FC and there was 11.87-59.65% reduction in number of tillers depending on stage of the plant. The shoot and root weights (fresh and dry), R:S ratio, total biomass and % DM were also affected. The reduction in shoot and root dry weights due to drought were up to 63.39% and 70.27% respectively. The effect of water stress on biomass can be very significant as there was a reduction in total dry biomass of up to 64.16%. The number of leaves and rate of increase in number of leaves, however, were not significantly affected by availability of water. In the field environment, the height was reduced by 10.35%, heading was delayed by 17.23 days and the total biomass at harvest was reduced by 16.50% under rainfed conditions. Tillering-related traits were not affected if grown in rainfed condition except tillers plant^{-1}.

In the greenhouse experiment, the tillering-related traits, plant height, root and shoot fresh and dry weights and total biomass were significantly different in the 10 genotypes, where as the traits related to leaves were not significant. Genotype 12 was the earliest to have its first tiller emerged which was about 10 days earlier than Banks, had the highest shoot weight (fresh and dry) about 29.02% and 41.54% respectively and highest total biomass (fresh and dry) which was 25.78% higher than Banks. Genotype 11 had highest number of tillers which were 72.07% higher than Banks, highest rate of tiller production, 3.17 times that of Banks and highest root weight (fresh and dry) up to 30.13% higher than the control. In the field experiment, all the tillering-related traits, days to 50% heading and total biomass at harvest were significantly different among genotypes whereas the average height was not significantly different. Genotype 11 had highest number of tillers meter^{-1}, which is 30.18% higher than Banks, tillers plant^{-1}, 5 more tillers plant^{-1} than Banks and highest total biomass at harvest (38.63% higher than Banks).

The interaction effect of genotypes and the FC was not significant for tiller-related traits, leaf counts, plant height at 43 DAS, root and shoot weights, fresh R:S ratio and total biomass, but significantly affected plant height at 85 DAS and dry R:S ratio. In the field, the interaction between genotype and environment was significant for average height.

The best performing genotypes were impressive as these genotypes had the best traits measured in this study that could be the determinants of biomass yield. The total fresh and dry biomass in the greenhouse study were significantly correlated with shoot FW and DW, root FW and DW, rate of increase in plant height and number of tillers, plant height and number of tillers at 43 and 85 DAS. The high biomass of genotype 11 in the field can be attributed to high number of tillers meter^{-1} at 56 and 105 DAS, tillers plant^{-1} at 105 DAS as these were significantly and positively correlated with total biomass.

The high biomass genotypes like conventional rice were affected by drought and did better under flooded field conditions. However, some genotypes had comparable response under stress environments. The high biomass rice under stressed conditions that performed comparable to non stressed environments can be used for cultivation under stressed conditions to get optimum biomass yields. These results suggested that genotypes 11 and 12 are more tolerant to drought than the remaining genotypes. Genetic analysis and detailed characterization of both shoot and roots traits of these genotypes are needed to understand the inheritance pattern and the number of genes controlling the traits and determine specific leaves and root traits important in developing high biomass rice.

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